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DESIGN OF A PNEUMATIC FERTILIZER NESTING APPARATUS

by

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research, for acceptance, a thesis entitled DESIGN OF A PNEUMATIC FERTILIZER NESTING APPARATUS submitted by DARCY GEORGE MATHEW KUSLER in partial fulfilment of the requirements for the degree of MASTER OF SCIENCE.

Abstract

The objective of this thesis was to investigate the feasibility of modifying a pneumatic fertilizer applicator to place fertilizer in small nests rather than in continuous bands. To achieve the objective, two possible alternatives, namely, a rotary valve and an oscillating gate, were investigated. Both of these systems were installed separately on one branch of a Prasco Bandit pneumatic fertilizer applicator in order to analyse their effect on the overall system. The objective of analysing the effect of both the rotary valve and the oscillating gate on the total system was to attempt to introduce modifications which would not significantly alter the operation of the pneumatic fertilizer applicator.

An evalution of both the rotary valve and the oscillating gate were made using high speed photography. Analysis of the high speed films allowed determination of both the speed of operation and the distribution of fertilizer granules within the nest.

Acknowledgements

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SYMBOLS

A - area of pipe cross section (m^2)

β - coefficient of sliding friction ( )

c - axial component of particle velocity (m/s)

ΔC - increase of the mean particle velocity (m/s)

Cd - drag coefficient ( )

d - particle mean diameter (m)

D - pipe diameter (m)

f_1 - pipe friction coefficient for air = $\frac{\Delta P_1 \; 2 \; D}{L\rho_1 (U_1)^2}$

f_2 - pipe friction coefficient for solids = $\frac{\Delta P_2 \; 2 \; D}{L\rho_2 (U_2)^2}$

Fr - Froude Number = V/SQR[D g] ( )

F_1 - Froude Number = U_3/SQR[D g] ( )

g - acceleration due to gravity (m/s^2)

k - constant ( )

K_3 - arbitrary ( )

L - length along the pipe axis (m)

Δl - increments of length along line (m)

M_0 - mass flow ratio = Q/M ( )

M - mass flow rate of fluid (kg/s)

ΔP_1 - pressure drop due to clean air (Pa)

ΔP_2 - additional pressure drop due to the presence of solids (Pa)

ΔP_3 - pressure drop due to acceleration (Pa)

ΔP_4 - total pressure drop (Pa)

Q - air mass flow rate (kg/s)

R_1 - Reynolds number defined as: $d(U_3\rho_1/u)$ ( )

R_2 - Reynolds number defined as: $d(U_1 - U_2)\rho_1 / u$ ( )

SQR - square root of [ ]

u - fluid viscosity (N s/m^2)

U_0 - actual fluid velocity = U_1/ϵ (m/s)

U_1 - average velocity of air over the pipe cross section (m/s)

U_2 - average solid velocity over the pipe cross section (m/s)

Ut - terminal velocity of a single particle (m/s)

V_0 - average velocity ratio of solids to air U_2/U_1 (m/s)

V_1 - minimum transport velocity (m/s)

V_2 - settling velocity in an infinite fluid SQR[4 g d $(\rho_4 - 1)/(3$ Cd)] (m/s)

Ws - solid flow rate (kg/s)

ϵ - voidage in transport lines ( )

ρ_1 - air density (kg/m^3)

ρ_2 - particle density (kg/m^3)

ρ_0 - air density where V_2 was measured (kg/m^3)

Ø - inclination of the pipe (degrees)

1. Introduction

Rising fuel and fertilizer costs have been instrumental in creating an interest in efficient fertilizer use. Experience has shown farmers that the application of fertilizers can significantly increase crop yields. However, high levels of certain fertilizers can cause severe damage to the crop if applied with the seed. Nitrogen fertilizers are among the fertilizers which will cause plant damage if applied with the seed at high rates.

To prevent damage, many farmers have altered their field practices to applying nitrogen fertilizer as a separate operation from seeding. One of the first methods employed to apply fertilizer as a separate operation from seeding was broadcasting. Broadcasting offered the simplest, cheapest, and quickest method of applying larger amounts of fertilizer without damaging the seeded crop, and without investing significant capital in additional sophisticated equipment. If the broadcasting operation was done just prior to seeding the farmer would often unknowingly incorporate the fertilizer while doing the seeding operation. As research continued, soil scientists realized this incorporation of fertilizer was important and resulted in more efficient use of the fertilizer by the grown crop. Researchers also discovered that fall broadcast fertilizers did not produce results equivalent to spring broadcast fertilizers. The lower return from fall broadcast fertilizer was improved when the fertilizer was also incorporated in

the fall, but spring broadcast and incorporated fertilizer resulted in significantly better results in the fall harvest. Why was there an interest in applying fertilizer in the fall? As soon as researchers and farmers realized large amounts of fertilizer would have to be applied separately from the seed, attempts were made to optimize the separate operation. In western Canada fertilizer prices are generally lower and field conditions are generally drier in the fall than in the spring. Since farm labour requirements are also usually lower in the fall than labour requirements in the spring, many farmers are applying nitrogen fertilizer in the fall.

Recent research by many respected researchers has shown that yield can be significantly increased if fertilizer is banded during application. The higher efficiency which results from banding fertilizer has induced manufacturers to produce a number of machines specifically for banding, or multipurpose machines which can be used for banding fertilizer and seeding cereal crops.

Pneumatic systems have a number of characteristics which are advantageous in this application. To begin with a number of the systems can be used with an existing cultivator. This lowers the investment required by the farmer and results in a banding unit which has the same working width as the farmer's cultivator. Since farmers generally size their cultivators as large as possible for their available field power, these systems give the farmer a

larger and therefore faster system than could be justified solely for banding fertilizer (figure 1.1). Secondly, most pneumatic systems have large storage tanks which minimize the number of required filling stops, particularly when high application rates are being used (figure 1.2). Furthermore, by using a cultivator as the application tool, fall banding can be combined with fall field work thus reducing the number of required field operations.

The most recent research in the field of nitrogen fertilizer application has been in the area of nesting or double banding. Nests are created when the fertilizer for a band is collected over a short distance (approximately 0.3 metres), then placed at one point. If banding is defined as concentrating the fertilizer in one dimension, nesting might be considered double banding in that fertilizer is concentrated in two dimensions. Early indications are that nesting may result in an even higher yield than a banded application at the same rate. Studies so far have been done by hand because no equipment has been available to place nests in the soil.

Figure 1.1 Pneumatic fertilizer bander on a field cultivator

Figure 1.2 Refilling storage tank on a pneumatic fertilizer bander

2. Literature Review

2.1 Fertilizer Placement

Recently published experiments conducted by Nyborg et al (1979) showed that fall application of urea (46% nitrogen) in constricted nests produced higher yields than fall application of urea in bands. More specifically in five field experiments conducted between 1977 and 1979 in northern Alberta and northern Saskatchewan, yields with fall incorporation, fall banding, fall nesting, and spring incorporation were 960, 1240, 1560, and 1830 kg/ha, respectively. Note that both fall banding and fall nesting of fertilizer resulted in much better yields of barley than did the fall incorporation of fertilizer. However for northern Alberta and northern Saskatchewan, spring application of fertilizer produced the highest yields of barley.

Interestingly, research reported by Harapiak (1979) did not find spring application of fertilizer by any method to produce the highest yield. In fact, when Harapiak summarized data for field trials conducted primarily in the southern portions of the prairie provinces, fall banding was found to be superior to both spring broadcasting and spring banding of fertilizer. More specifically Harapiak rated late fall broadcasting, late fall banding, spring broadcasting, spring banding, and post planting applications of fertilizers as

95, 120, 100, 115, and 75 respectively.

The seeming conflict between Nyborg et al's results, obtained primarily in northern Alberta and Harapiak's results, obtained primarily in the southern portions of the prairie provinces, can be accounted for by examining the soil moisture conditions for each research project. According to Harapiak, the loss of soil stored moisture during the extra spring tillage associated with any spring fertilizer application could be the reason fall banding was superior to spring banding in the southern areas. Soil moisture levels might have a far greater effect on yields in the drier southern regions of the prairies than they would have on yields in the more moist northern soils.

Nyborg and Leitch (1979) suggested a second possible explanation for the seemingly random results from experiments comparing spring and fall fertilizer applications.

> *The inferiority of fall applied N fertilizer found in northern Alberta, but not reported in southern Alberta, may be related to more severe N deficiency in the north and to more saturation of the northern soils during the spring thaw. Losses of N through leaching and denitrification occur only with nitrate, and not with ammonium.*

The authors went on to explain:

> *The losses of fall-applied N seem mostly to take place when the soil is first thawed and saturated in spring, and fall-applied urea is usually only partly nitrified by that time...*

These statements agree well with Malhi (1978) who explained some aspects of the nitrification process. Field and laboratory data lead Malhi to suggest ammonification and nitrification occur throughout the winter, leading to large amounts of NO_3 just prior to spring thaw. During the spring thaw, the water saturated condition of the soil (which is common in northern Alberta) above the frozen layer leads to relatively rapid denitrification of the accumulated NO_3.

Leitch's (1973) findings showed nitrification of N fertilizer could be slowed by application in bands. Through-out the prairie provinces Ridley (1977), Malhi (1978), Harapiak (1979), and Nyborg et al (1979) all noted fall banding of N fertilizer gave higher yields than did fall incorporation of fertilizer with the soil.

The mechanism which slowed nitrification of N fertilizer in bands was probably the same mechanism which slowed nitrification in nests. In fact, nesting could be explained as double banding, or banding in two directions. The increased yield which results from the use of nests, can be simply explained by a double banding effect. Following this train of thought, nesting might be expected to increase yields above those of banding in any area where banding of N fertilizer increased yields above those of incorporation.

Also of interest are the urea "super granules" produced for research by Norsk Hydro. Norsk Hydro's super granules which are produced for rice research, as noted by Holte et al (1982), are available in three different size ranges: one gram, two grams, and three grams. Interestingly, the available granule sizes are close to the nest sizes used by Nyborg et al (1979), and might be of interest for Canadian studies.

2.2 Fertilizer Placement Equipment

Nyborg et al (1979) conducted fertilizer nesting experiments utilizing hand placement methods. Results from those experiments were encouraging, but further research required some form of mechanization. The purpose of this thesis was to study the possibility of designing a fertilizer applicator capable of placing fertilizer in nests. A pneumatic fertilizer applicator was chosen as the base implement to modify into a fertilizer nester. Advantages such as high field capacity, operator convenience, and mechanical simplicity (making mechanical modification simpler) made the pneumatic fertilizer applicator an ideal experimental base piece of equipment. Since pneumatic conveying of material is the main principle upon which the pneumatic fertilizer applicators are designed, a literature review of pneumatic transport of particles was undertaken.

2.3 Pneumatics

2.3.1 Introduction to Pneumatic Conveying

Henderson and Perry (1976) describe pneumatic conveyors in the following way:

> *Pneumatic conveyors move granular material in a closed duct by means of a high-velocity stream of air. The advantages are: relatively low initial cost; mechanical simplicity (only one major moving part, the fan); conveying path can be random and may branch; conveying path can be changed easily; a wide variety of materials can be conveyed ... and the system is self cleaning.*

All of the above characteristics make application of pneumatic conveying to grain seeders and fertilizer applicators highly desirable.

2.3.2 Classifications

Before the science of pneumatic conveying can be analysed, a few classifications must be explained. According to Stankovich (1978) pneumatic conveyors can be grouped into three types: positive-pressure systems, negative-pressure systems, and negative-positive pressure systems. For the purposes of application on pneumatic fertilizer applicators only positive-pressure systems will be analysed. Positive-pressure systems of pneumatic conveying can be further sub-divided into dense-phase and dilute-phase

systems. Leung and Wiles (1976) defined dilute phase flow (or lean phase flow) as: (one)

> *in which the solids are carried upwards as an apparently even dispersed suspension with low volumetric solid concentration (generally less than about five per cent).*

Pneumatic fertilizer applicators operate within the dilute phase range.

2.3.3 Conveying in Straight Lines

When a material is transported pneumatically, the individual particles are not suspended in a laminar flow. Rather the particles are dropped into a turbulent air flow, where they are influenced by horizontal accelerations, rotational accelerations, and gravity. The net results of these accelerations are complex random paths. Individual particles collide with the walls of the conveying tube and with each other. Every one of these collisions results in an energy loss which may be perceived in a macro sense by a loss in static pressure. The loss of static pressure along a tube which is being used to transport material pneumatically can be split into three parts, namely:

1. pressure loss due to air alone,
2. pressure loss due to the presence of particles, and
3. pressure loss due to the acceleration of the particles.

Jotaki and Tomita (1971) define the total pressure drop in a conveying pipe into two parts; that due to friction

losses with the air alone (ΔP_1), and those additional losses due to the presence of solids (ΔP_2). Losses due to acceleration of particles (ΔP_3) were avoided by considering only a fully developed flow. The resulting formula [1]:

(1) $$\Delta P_4 = \Delta P_1 + \Delta P_2$$

- or -

(2) $$\Delta P_4 = \left[\frac{f_1 \rho_1 (U_1)^2}{2} + \frac{f_2 \rho_2 (U_2)^2}{2}\right] \left[\frac{L}{D}\right]$$

is quite simple and useful as defined. Ottjes et al (1976) and Scott et al (1976) both used equation (1) as their starting points. Scott et al (1976) went on to explore bend effects, which will be discussed later in this chapter. Ottjes et al (1976) added a term to describe the pressure loss due to the acceleration of the particles.

(3) $$\Delta P_4 = \Delta P_1 + \Delta P_2 + \Delta P_3$$

Generally, if ΔP_1 is assumed not be influenced by presence of particles, then

(4) $$\Delta P_1 = \frac{L f_1 \rho_1 (U_1)^2}{2D}$$

simply describes the pressure drop due to air alone. Similarly by using a simple relationship describing pressure

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[1] See the table of symbol definitions on page xvi

loss due to acceleration of the particles, ΔP_3 may be derived from the momentum equation. Ottjes et al (1976) described the relationship as:

(5) $$\Delta P_3 = \frac{Q\ \Delta U_2}{A}$$

Finally, a simple equation describing the relationship between pressure loss and the presence of particles in the air can be developed. Jotaki and Tomita (1971) described the relationship of pressure loss and the presence of particles in the air stream as:

(6) $$\Delta P_2 = \frac{f_2 \rho_2 (U_2)^2 L}{2\ D}$$

The above relationship was developed assuming suspended particles do not act exactly as a fluid does and the friction factor f_2 does not remain constant when the velocity of the particles changes.

2.3.4 Dimensional Analysis

McCabe and Smith (1967) explained dimensional analysis in part with the statement:

> *... if a theoretical equation does exist among the variables affecting a physical process, that equation must be dimensionally homogeneous.*

Researchers such as Reynolds and Froude found relationships

which held true as the variables within them changed. Reynolds developed the relationship:

$$R = \frac{\rho\ D\ V}{u}$$

which is the ratio of inertial forces to viscous forces. Any correlation developed which contains a Reynolds number may be applied to a different environment simply by supplying new values into the Reynolds number. Froude worked with the interaction of two fluids of different densities, and discovered the effect of gravity was nearly always important. Ship designers have been long time users of Froude's relationship:

$$F = \frac{V}{SQR(gL)}$$

which allows models and studies of the effect of water on a ship's hull to be done. Similarly a relationship must exist between a suspended particle and the fluid or gas within which the particle is suspended. More recently Rizk (1976) related pressure drops to the Froude numbers of the suspended particles. Yang and Keairns (1976) developed a solid particle friction factor which used Reynolds numbers and could have used a Froude number.

For Vertical Conveying

$$(7) \qquad f_2 \frac{\epsilon^3}{(1-\epsilon)} = 0.0206 \left[\frac{(1-\epsilon)(R_1)}{R_2}\right]^{-0.869}$$

For Horizontal Conveying

$$(8) \qquad f_2 \frac{\epsilon^3}{(1-\epsilon)} = 0.117 \left[\frac{(1-\epsilon)(R_1)}{R_2} \frac{U_0}{SQR[gD]}\right]^{-1.15}$$

- or if a Froude number were used -

$$(8.1) \qquad f_2 \frac{\epsilon^3}{(1-\epsilon)} = 0.117 \left[\frac{(1-\epsilon)(R_1)}{R_2} F_1\right]^{-1.15}$$

The separate relationships developed by Yang and Keairns (1976) for horizontal and vertical conveying are worthy of note. As can be seen above, the relationship for horizontal conveying is more complex than the relationship for vertical conveying. The simplest explanation for the simplicity of the vertical term is the fact that the particle's plane of movement is the same as the direction of the earth's gravity.

2.3.5 Acceleration of Particles

The pressure drop experienced due to the acceleration or re-acceleration of particles in a pneumatic conveying system is of paramount importance in a pneumatic fertilizer applicator. Scott et al (1976) noted that with the 0.100 m diameter tube used in their research

> *the majority of the re-acceleration appeared to take place within 9.0 metres after a bend.*

No tube on present day pneumatic fertilizer applicators has a length which is straight for 9 metres. That means that particles in a pneumatic fertilizer applicator will always

be accelerating. Yang and Keairns (1976) described the pressure drop during acceleration as:

$$(9) \qquad \Delta P = \int_0^L \rho_2 (1-\epsilon) dL + \int_0^L \frac{2 f_1 \rho_1 (U_1)^1}{g\ D} dL + \int_0^L \frac{f_2 \rho_2 (1-\epsilon)(U_2)^2}{2\ g\ D} dL + \left[\frac{\rho_2 (1-\epsilon)(U_2)^2}{g}\right] \mathit{at}\ L$$

2.3.6 Bends

The effect of a bend in a pneumatic transport line extends not only over the bend itself, but also over the downstream straight section where the particles are re-accelerated. Scott et al (1976) showed significant pressure drops after the bend (figure 2.1). Complete steady flow was not re-established for 15 metres downstream, although the majority of the re-acceleration appeared to take place within 9 metres of the bend. Since a 0.100 metre diameter tube was used in the experiment, the results might be applied directly to pneumatic fertilizer applicators which use 0.100 metre diameter tubes to transport material up to the primary manifolds.

Page 16 has been removed because of copyright restrictions, the illustration is available from Scott et al (1976).

"The extra pressure drop attributed to a bend"

2.3.7 Slope

Researchers have been working with vertical and horizontal pneumatic conveying systems for years, but little interest was shown in tubes at angles between horizontal and vertical. Duckworth (1976) investigated the effect of duct slopes on the minimum transport velocity required. The results of Duckworth's investigation are somewhat surprising. When a ratio of minimum transport velocity to settling velocity was studied at different conveying tube angles, the results showed an increase in required minimum transport velocity as the conveying tube angle increased. The required transport velocity reached a maximum at 45 degrees of conveying tube angle and began to decrease as the tube angle continued to increase. Duckworth provides a number of charts from which values can be selected, but only gives the relationship as a function of the ratio of particle diameter to duct diameter and angle of elevation:

$$(10) \quad V_1/V_2 = \text{function}_2(d/D) \times \text{function}_2(\varnothing) \times M^{0.3}$$

2.3.8 Minimum Required Air Flows

When a pneumatic conveying tube does not have sufficient air velocity and pressure to keep the particles evenly distributed throughout the cross-sectional area of the tube, the particles begin to settle to the lower half of the tube. Scott (1978) realized that some pneumatic

conveying applications might take place within these conditions. As a result, Scott developed two formulae to describe the movement of the particles in an air stream. The first:

$$(11) \quad \Delta P_2/\Delta l \times A/F_2 = \frac{\beta\ g}{\left[U_1 - V_2 SQR[\beta(\rho_0/\rho_1)]\right]}$$

describes the pressure loss per unit length when the transport velocity is not sufficient to keep the particles suspended in the entire cross-sectional area of the tube (i.e. the particles are in the lower half of the tube only). The second:

$$(12) \quad \Delta P_2/\Delta l \times A/F_2 = \frac{K_3\ V}{D\left[1 + W_1\ SQR\left[\frac{4K_3\rho_0}{gD\rho_1}\right]\right]}$$

describes the pressure loss per unit length when the transport velocity is high enough to keep the particles distributed evenly across the conveying tube's cross-sectional area.

Estimation of minimum air flows required to move required mass flow rates in a pneumatic system is of great importance in order to properly size ducts and fans. Unfortunately many present methods require the system to be built, then the air flow rate determined experimentally.

Rizk (1976) developed a simple relationship:

(13) $$M = K\,Fr^{4}$$

which relates mass load ratio to a Froude number. Since the Froude number relates air velocity to pipe diameter, Rizk's relationship allows an air flow to be chosen for a required mass flow rate and pipe diameter.

3. Preliminary Studies

3.1 Field Equipment

Prior to beginning any experimental work, a field study was conducted by the author to examine pneumatic seeders and pneumatic fertilizer applicators marketed in western Canada. The John Deere, Prasco, Wil-Rich, Morris, and Friggstad were studied and a large number of common characteristics were determined. Without exception each pneumatic system utilized some form of a field cultivator to place material into the ground. The pneumatic seeders and fertilizer applicators were either mounted directly on the cultivator frame (as was Wil-Rich for example) or were located between the tractor and the cultivator (as were Prasco and John Deere). All the pneumatic systems had large tanks for seed and/or fertilizer, thus diminishing the number of refilling stops required during field operations.

A large fan was used on each pneumatic unit to supply an air stream within which the fertilizer and/or grain could be suspended. These fans were driven by one of three methods:

- a separate engine mounted on the pneumatic device (figure 3.1),
- a power take-off shaft from the tractor (figure 3.2),
- or a hydraulic motor mounted on the fan and operated by the tractor's hydraulic system (figures 3.3 and 3.4)

Figure 3.1 Fan driven by a separate engine

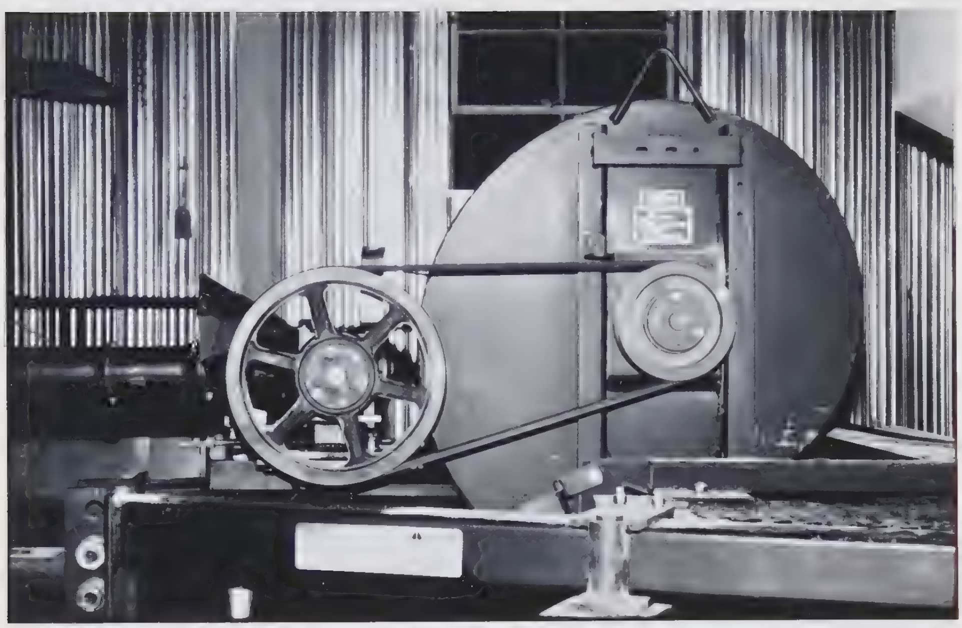


Figure 3.2 Fan driven by a power take-off shaft

Figure 3.3 Hydraulically driven fan

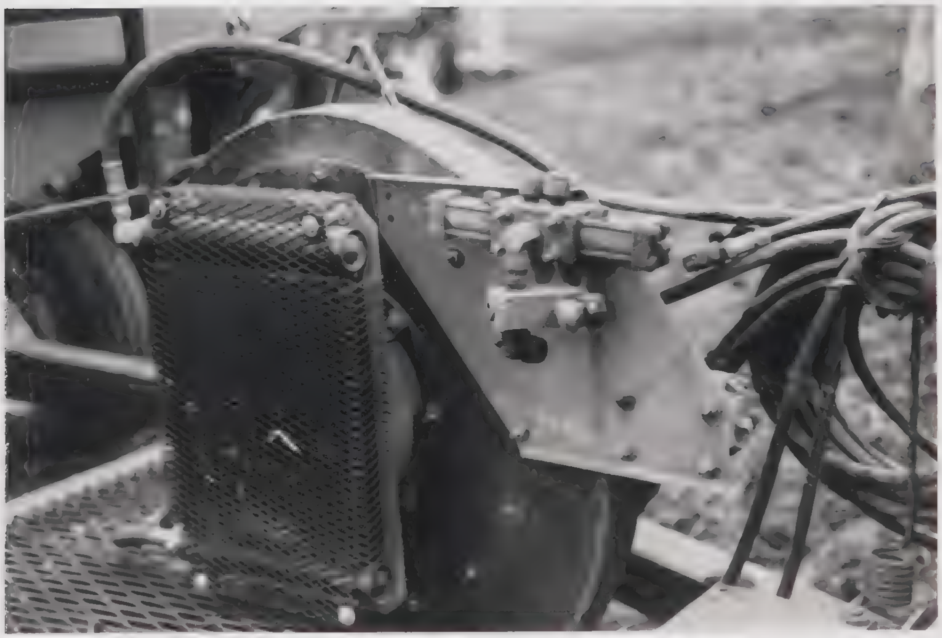


Figure 3.4 Oil cooler required by hydraulically driven fans

Of the three systems, the power take-off system is the simplest and the cheapest, but power take-offs are not always available on large four wheel drive tractors. Therefore most companies offer one of the other two drive systems as standard or an option.

Only Wil-Rich divided the air flow into individual lines for each seed or fertilizer row prior to the point where the seed and/or fertilizer were introduced into the air stream. The remainder of the manufacturers introduced the seed and/or fertilizer into one or more primary air streams, then used flow dividing manifolds to distribute the air-solid mixture to individual cultivator shanks.

3.2 Objectives

Since research in the area of fertilizer application indicated there was an advantage in applying fertilizer in nests, the purpose of this thesis was to develop a laboratory prototype to apply fertilizer in nests. A pneumatic fertilizer applicator seemed to be a logical base machine from which to start, because the air conveying lines could easily be moved around, simplifying modification.

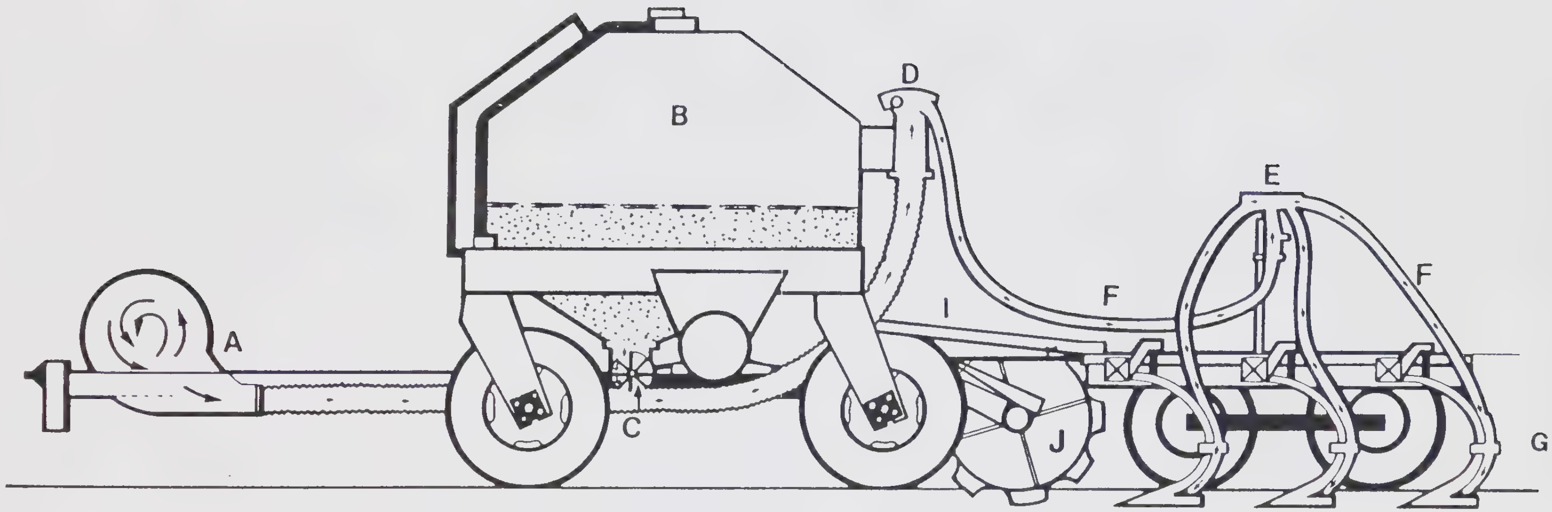
4. Experimental Procedure

4.1 Test Equipment

A Prasco Bandit[2] was obtained as a base machine to develop a prototype. Simplistically (figure 4.1), the Prasco Bandit consisted of a fan, a number of tubes, a hopper, a metering device, two flow dividers consisting of a primary manifold and a secondary manifold, and a number of soil engaging boots. The fan supplied air at a high velocity into a 100 mm diameter duct located below the hopper. Fertilizer was dropped from the hopper into the high velocity air by the metering device. Once the fertilizer was in the duct, it was pneumatically transported to the primary manifold. There the duct was divided into five 50 mm diameter tubes that were balanced, thus creating equal flow rates of air and suspended fertilizer in each tube. Each of these tubes carried the suspended fertilizer to a secondary manifold. At the secondary manifold, each tube was again subdivided into ten 25 mm diameter boot tubes, which carried the suspended fertilizer to the soil engaging boots. Fertilizer was then deposited into a band within the soil by the openers.

The Prasco Bandit was delivered to the University of Alberta equipped with a 16.7 revolution per second power-take-off driven fan, which was coupled directly to a

[2] The Prasco Bandit was a pneumatic fertilizer banding machine produced by Prasco Super Seeder Ltd., Drumheller, Alberta and loaned to the University of Alberta for this study.



A. Blower
B. Storage tank
C. Metering device
D. Primary manifold
E. Secondary manifold
F. Flexible tubing
G. Boot

Figure 4.1 Simplified diagram of a pneumatiac fertilizer bander

20 revolution per second 29 kW electric motor. Provision for three fan speeds was made by changing the size of the driven pulley on the fan.

An intake air duct was constructed in accordance with the Fan Engineering Handbook and was equipped with a flow straightener as recommended by Jorgensen (1961) and ASHRAE standard 51-75 (figure 4.2). A Sierra model 435-2 hot-wire anemometer was used to measure the velocity of air flowing through the duct, allowing the quantity of air entering the fan to be calculated. Fertilizer having passed through the Prasco unit was then collected in plastic containers, located where the soil engaging boot would normally have been.

One tube which would have been connected to a soil engaging boot in a field application, was modified to allow the flow of fertilizer to be photographed. This modification consisted of replacing the last 150 mm of the tube with a clear acrylic tube. Care was taken to keep the diameters and lengths of the tubes to those found in field applications. During high speed filming, which was done at 250, 300, and 400 frames per second, the film was marked each 1/10 of a second to allow film speed (frames per second) to be checked and to provide a time frame for particle travel.

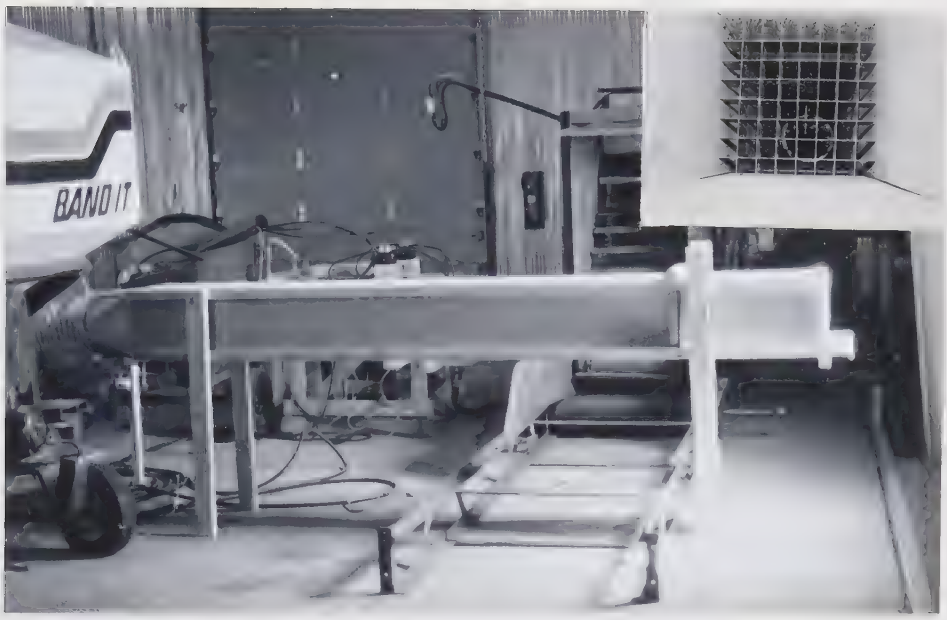


Figure 4.2 Air intake duct with a flow straightener shown in insert

4.2 Fertilizer Properties

Urea was the form of fertilizer used for experiments within this thesis project. Aeron (1978) described urea as

> *... a synthetic organic nitrogenous fertilizer made by combining liquid ammonia and liquid carbon dioxide at very high temperatures and pressures. The product in final form is prilled and contains forty six per cent nitrogen.*

Two different granule sizes of urea were included in this experiment. The first granule size was that of standard agricultural urea as available from local farm distributors. A sieve analysis (appendix A-1) netted a geometric mean diameter of 1.8 millimetres following a procedure similar to ASAE standard S319.[3] Throughout this thesis the agricultural urea granules are referred to as "small urea granules" or as "small granules".

The second granule size tested was that of forestry grade urea. Forestry grade urea was developed in large granules for the forest industry where the fertilizer must be spread on the land surface and left exposed to the natural elements. A sieve analysis of the forestry urea (appendix A-2) netted a geometric mean diameter of 2.9 millimetres following a procedure similar to ASAE standard S319. Throughout this thesis the forestry urea granules are

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[3]ASAE standard S319 is a test procedure to determine the fineness of feed ingredients and to define a method of expressing the particle size of the material. Since no such standard exists for agricultural fertilizers, a procedure similar to S319 was used.

referred to as "forestry urea" or simply as "large granules". The two granule sizes may be compared in figure 4.3.

Holte et al (1982) discussed "super granules" which are larger sizes of granular urea available on the international market from Norsk Hydro. Super granules are very regularly shaped 1, 2, and 3 gram granules of urea. Although these very large granules have only been used in tropical research until now, and were not used in this thesis, they may be of interest to future North American researchers.

4.3 Modifications

4.3.1 Rotary Valves

Initially a rotary valve seemed to be the simplest means of interrupting the pneumatic flow of fertilizer. By replacing the secondary manifolds of the Prasco Bandit with rotary valves, the fertilizer would be introduced into the tubes to the boots for one time period in ten, but at a rate equal to ten times the normal rate. The combination of the temporary high rate and short time period would theoretically result in an application rate equal to that through a normal manifold, but the material would be introduced only into ten percent of the normal length of the band. The first prototype was produced by modifying an existing secondary manifold (figure 4.4). Fertilizer

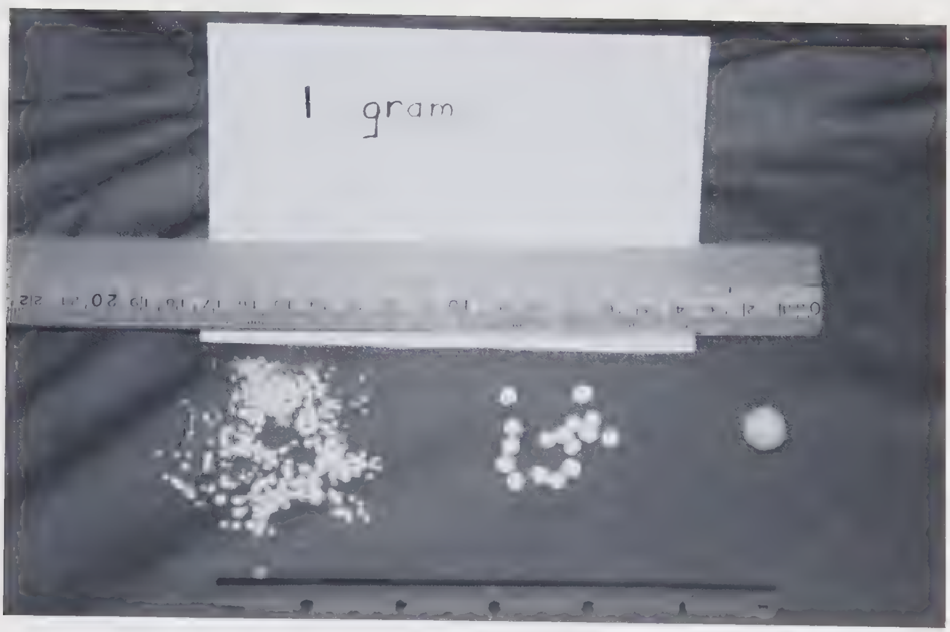


Figure 4.3 Comparison of fertilizer granule sizes

Figure 4.4 Rotary valve

entering through a 50 mm diameter intake was directed out one of the ten 25 mm diameter exhaust ports, then the valve was rotated, blocking the first exhaust port and opening a second.

Each of the ten exhaust ports was opened then closed sequentially, resulting in each port being open 10 percent of the time. Unfortunately with the rotary valve replacing one secondary manifold, the available exhaust area for that secondary manifold was reduced by 90 percent and the total branch from the primary manifold blocked.

A second rotary valve was designed to solve the blocking problem caused by the exhaust restrictions of the first rotary valve prototype. Fifty millimetre diameter tubes were chosen for both the intake and all the exhaust ports of the rotary valve. Two exhaust ports were drilled into the rotating center core of the rotary valve. These exhaust ports were not quite symmetrical in the central rotating core. Rather, the ports were placed in such a way that as one port began to open, the other port began to close. In this way a 50 mm diameter exhaust port was always available, and the blocking problem was solved.

When the blocking problem had been solved, the last 150 mm of one of the boot tubes (tubes from the rotary valve's exhaust ports) was replaced with 50 mm diameter clear acrylic tube and high speed films were taken of the interrupted flow.

4.3.2 Oscillating Gates

A second method of producing fertilizer nests was attempted by designing a device which would collect the fertilizer granules for a nest, then release them as a clump. One of these devices would be required for each boot tube, and each would be mounted at the top of the boot. Because of the number of devices required for a large field unit and the hostile environment in which the device would operate, a simple sturdy design was sought. Further, with a nest required each 0.3 metres of field travel and a field speed of at least 5 km/h, a nest would have to be released each 0.2 seconds.

To meet the above requirements a simple air-particle separator with an oscillating gate at its base was developed. The air-particle separator allowed the transporting air to escape and the fertilizer granules to come to rest on the gate at the device's base. When sufficient time had passed, the gate was rapidly pulled out of the way to one side, and the clump or nest of fertilizer fell into the boot.

An electrical solenoid was chosen to pull the gate open (while a spring reclosed the gate) to keep the project simple and to allow the system to operate within the required time frame. Another advantage of using the electrical solenoid as the driving device was the use of a simple electronic circuit control to drive the solenoid directly. No hydraulics or pneumatics were required to

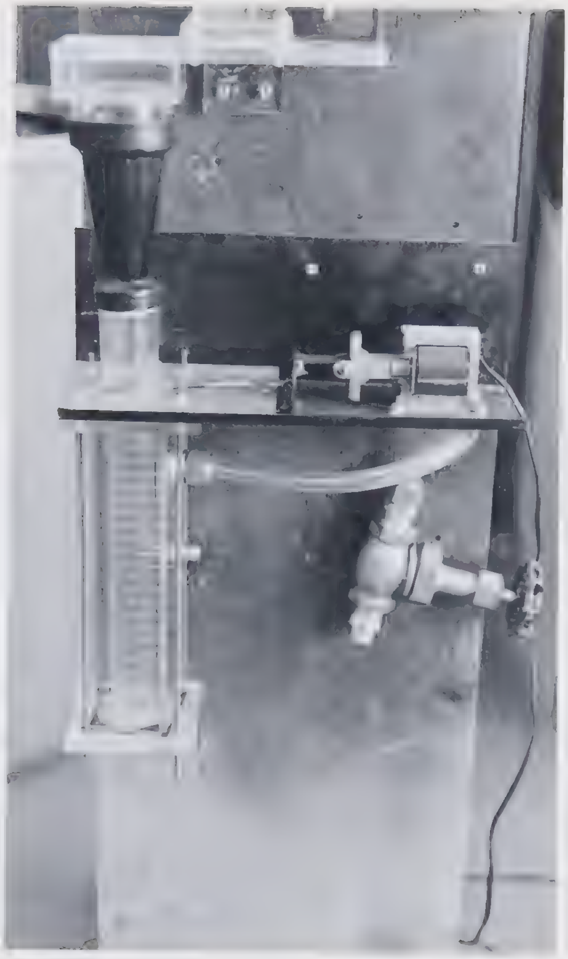
operate the oscillating gate. Duration and frequency of the gate opening were controlled initially by a timing circuit, and later by a P.D.P. 11 mini-computer (figure 4.5).

The air-particle separator was made by introducing the boot tube (25 mm diameter) into a 50 mm diameter tube. Increasing the cross-sectional area caused a rapid decrease in air velocity. The lower velocity air was not capable of holding the fertilizer granules in suspension, and the granules fell to the bottom of the separator. Conveying air was then forced to reverse direction (to ensure no particles were still suspended) and allowed to escape to the atmosphere unhindered. Falling fertilizer particles were funnelled into a 25 mm diameter tube and came to rest on the gate located at the base of the air-particle separator. When sufficient time had elapsed the solenoid was activated and the gate momentarily opened, dropping the nest of fertilizer granules into the short boot (figure 4.6). Very short open durations did not allow all the material on the gate to fall through and blocking resulted. Once the open duration requirements were filled, the maximum available frequencies at which the gate could perform the intended function were limited.

Figure 4.5 P.D.P. 11 mini-computer

A

B



C

D

E

A. Air-particle separator

B. Funnel

C. Electrical solenoid

D. Oscillating gate

E. Clear boot tube to allow filming

Figure 4.6 Oscillating gate and electrical solenoid

5. Instrumentation

5.1 Power

5.1.1 Polyphase Wattmeter

A Weston polyphase wattmeter model 329 was used to measure the electrical energy consumed by the electrical motor driving the fan. The Weston wattmeter is of the electrodynamometer type, shielded from the effects of external magnetic fields, and temperature compensated. Two Weston model 461 current transformers were used in conjunction with the wattmeter to lower the current flowing through the wattmeter (figure 5.1).

5.1.1.1 Calibration

Published data with the Weston wattmeter claims an accuracy of one-half of one per cent of a full-scale value for any frequency up to 125 hertz. The Department of Electrical Engineering at the University of Alberta checked the calibration of the wattmeter prior to the beginning of the experiment, and the zero of the meter was checked prior to each run. Field connections and the effect of the current transformers combined to give a motor factor of 80. Power consumed by the electrical motor could then be calculated (in watts) by multiplying the motor factor by the scale reading on the wattmeter.

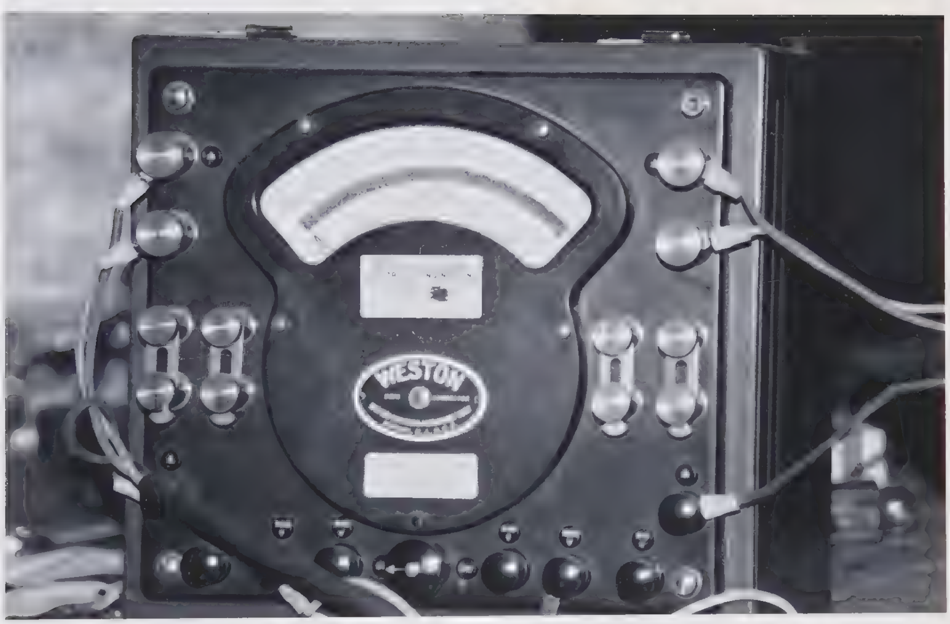


Figure 5.1 Weston wattmeter

5.2 Velocities

5.2.1 Air Speeds

5.2.1.1 Intake Air Duct

The intake air duct was constructed in accordance with the Fan Engineering Handbook and was equipped with a flow straightener as recommended by Jorgensen (1961) and ASHRAE standard 51 - 75.

Calibration

To calibrate the air duct, readings were taken at 36 individual locations and a correction factor calculated for the duct's center reading.

5.2.1.2 Sierra Anemometer

A Sierra model 435-2 hot wire anemometer (Sierra Instruments, Redland, California) produced by Kurtz was used to measure air speed inside the intake air duct. The Sierra anemometer's output was one volt for each 1.27 m/s (250 feet per minute) of air speed which passed the sensor. This voltage was fed to a Sanwa model SH-63TR analog voltmeter. The Sanwa was re-zeroed prior to each run and could be read to the nearest 0.1 volt.

Calibration

The Kurtz Sierra model 435-2 hot wire anemometer was calibrated by Sierra Instruments, Redland, California on the 27th day of the 5th month of 1982.

5.2.1.3 Pitot Tube

Air velocities were measured downstream from the fan using a pitot tube similar to those described by ASHRAE standard 51-75. The pitot tube was fastened concentrically inside a second tube of slightly larger diameter which received static pressure from radial sensing holes around the tip. When impact pressure was connected to one leg of a manometer and static pressure connected to the other leg of the manometer, the velocity pressure was indicated directly.

Calibration

The pitot tube used was similar to the description in ASHRAE 51-75 and as such was considered a primary instrument, which requires no calibration.

5.2.2 Rotational Velocities

5.2.2.1 Pioneer Digital Stroboscope

The model DS-303 Pioneer digital stroboscope was used to measure the rotational velocities of the electric motor and the actual rotational velocity of the fan while under test. Pioneer literature supplied with the stroboscope states an accuracy of plus or minus one revolution per minute (figure 5.2).

Figure 5.2 Pioneer digital stroboscope

Calibration

The calibration of the digital stroboscope was checked by two methods. First, a 60 hertz power line frequency was supplied to one channel of a Tectronics model 432 dual trace oscilloscope. Then the triggering voltage from the stroboscope, which was set at 60 hertz, was supplied to the second channel of the oscilloscope. Comparison of the two traces resulted in no perceivable timing difference.

A second calibration check was done using a one kilohertz calibration signal from the Tectronics model 432 dual trace oscilloscope. When the one kilohertz signal was compared to 14,955; 29,907; and 19,939 rpm triggering signals from the stroboscope, ratios of 1/4, 1/2, and 1/3 respectively were obtained. Theoretically that gave the stroboscope an error of 0.3 percent.

5.2.2.2 Hasler Tachometer

Low speed rotational velocities were measured by means of a model 15228 Hasler hand-held tachometer. Readings were made by holding the tachometer in direct contact with the shaft whose speed was being measured, then activating the tachometer. Once the measurement was made the dial of the instrument remained stationary and the instrument could be moved to allow for more convenient reading.

Calibration

The calibration of the Hasler hand-held tachometer was checked against the Pioneer digital stroboscope. Ten rotational velocities were chosen between 8.33 r/s (500 rpm) and 16.7 r/s (1000 rpm). Each rotational velocity was read with the Hasler hand-held tachometer, then the Pioneer stroboscope. Both readings were recorded and an error calculated for each rotational velocity. The largest recorded error was 0.67% for the Hasler tachometer at 9.93 r/s (596 rpm).

5.3 Pressure

5.3.1 Manometers

Manometers were fabricated in U shapes from 8 mm glass tubes. Each manometer was filled with distilled water and a small amount of food coloring was added. The manometers were mounted vertically on a scale which could be read to the nearest millimetre (figure 5.3).

5.3.2 Static Pressure

Static pressure was measured by connecting a tube between a static pressure tap and one leg of a liquid manometer.The second leg of the manometer was left open to atmospheric pressure. Care was taken when placing static

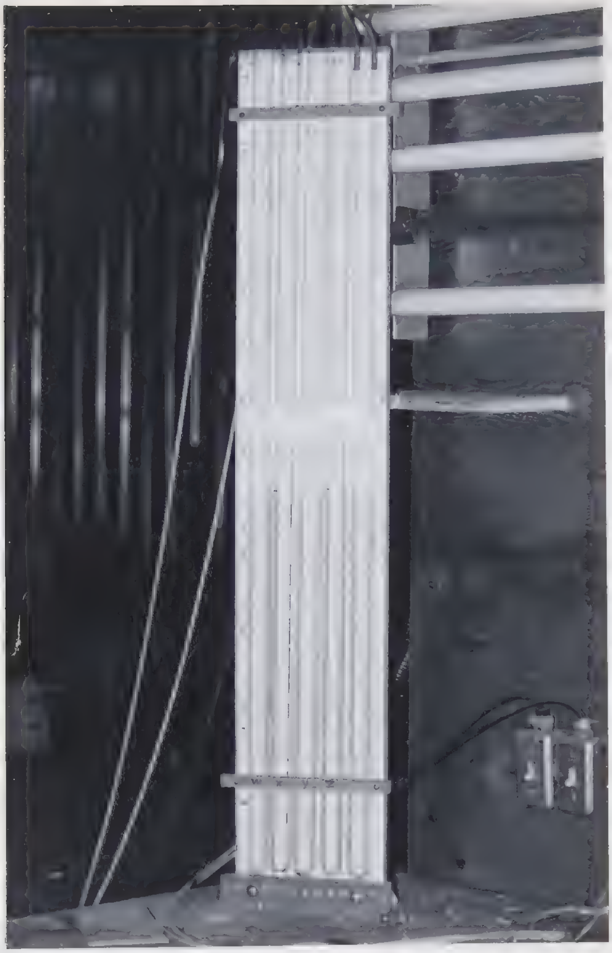


Figure 5.3 Manometers

pressure taps to prevent anything from intruding into the tube to disturb the internal flow patterns.

5.3.3 Barometric Pressure

Barometric pressures were obtained during each test from the meteorological observatory of the Atmospheric Environment Service located at the International Airport, Edmonton,Alberta.

5.4 Temperature

Both wet and dry bulb temperatures were taken by a Cenco sling psychrometer. The scales on the thermometers could be read to the nearest degree Celsius. Wet bulb temperatures were measured by placing a moistened wick over the bulb of the wet bulb thermometer. Internal temperatures within the system were taken with a Celsius thermometer similar to those mounted on the Cenco sling psychrometer, by introducing the thermometer into a static pressure tap.

5.4.1 Calibration

As suggested by ASHRAE standard 51-75 the thermometers were calibrated over the range of temperatures encountered during tests against a thermometer with a calibration that was traceable to the National Bureau of Standards. Maximum error recorded was 0.4 degrees Celsius for the single thermometer and 1.4 degrees Celsius for the thermometers on the sling psychrometer.

6. Results and Discussion

6.1 Pneumatics

Plans of doing a detailed study of the actual pneumatic transport of fertilizer granules within the pneumatic fertilizer bander had to be abandoned. Although a good deal has been written on the topic of pneumatic transport of industrial products in recent years, very little information is available on the pneumatic transport of agricultural products. Additionally, much of the existing pneumatic transport information published for agriculture is quite old and assumes particle friction coefficients do not vary with air velocity or conveying tube diameter. In contrast Rizk (1976) suggested:

> *The most complicated form of pneumatic transport is that in horizontal pipes. ...This region is characterized by means of the physical properties of the solid particles and of the pipeline together with the velocities of both gas and solids, and the mass flow ratio and mass concentration.*

Examination of the pneumatic section of the literature review revealed many characteristics of fertilizer must be known before a detailed study of a complex system (such as a pneumatic fertilizer applicator) might be undertaken. Three of the required characteristics of fertilizer which were unknown in this experiment were:

- terminal velocity of a single particle,
- actual particle velocity (which is very difficult to measure),
- and the particle's pipe friction coefficient.

Establishing these unknowns would be a thesis project of its own and for that reason no actual pneumatic study was undertaken within this thesis. However since the author believes a study of handling fertilizer pneumatically should be undertaken, a literature review of pneumatic conveying has been included in this thesis. Recorded pressure drops along the pneumatic conveying lines have also been included in appendix H.

Attempts were also made to measure air velocities downstream from the fan. ASHRAE standard 51-75 requires air velocities only be measured ten tube diameters downstream from the fan. Unfortunately no section of the Prasco's fertilizer transport tube was straight for ten tube diameters. Therefore velocity pressures were measured in two locations downstream from the fan using non-standard methods. The first traverse plane (referred to as W) was located as close as practical to the fan and before the metering device. The second traverse plane (referred to as Y) was located 1.8 metres downstream from the first traverse plane and 1.25 metres downstream from the metering device. A forty five degree bend was located along the 1.8 metres of fertilizer conveying tube separating the two traverse planes causing traverse plane Y to be located on a conveying tube

sloped at forty five degrees from the horizontal. Two traverse paths intersecting at ninety degrees were made across the duct at each traverse plane and fourteen velocity pressures were recorded at equal intervals along each traverse path. (Data from the velocity pressure traverses are given in appendices J-1 and J-2.)

6.2 Rotary Valves

Initially a rotary valve seemed to be the simplest means by which to interrupt the pneumatic flow of fertilizer. By replacing the secondary manifolds of the Prasco Bandit with rotary valves, the fertilizer would be introduced into the lines to the boots for one time period in ten, but at a rate equal to ten times the normal rate. The combination of the temporary high rate and short time period was to result in an application rate equal to that through a normal manifold, but the material would be introduced into only ten per cent of the normal length of the band. The first prototype was produced by modifying an existing secondary manifold, which had a 50 mm diameter round intake and ten 25 millimetre diameter round exhaust ports. Unfortunately, with the rotary valve in place, the system only had one 25 mm diameter exhaust port available at any one time. On a pneumatic system designed for ten 25 mm diameter exhaust ports, one exhaust port acted as a block, and the total branch to the modified manifold blocked.

Analysis of the system quickly showed the blocking problem was caused by the reduction of the exhaust port area by nearly ninety per cent. A second rotary valve was then developed which constantly had a cross-sectional exhaust area open equal to the manifold intake area. Test runs with this device indicated the blocking problem had been solved. Next, one exhaust port from the rotary valve was connected to a clear tube located in the boot's location in order to allow the clump of material flowing from the rotary valve to be filmed.

Examination of the high speed films of the material from the rotary valve showed almost no clumping effect. Evidently the material introduced into the boot tube at the rotary valve as a clump had redistributed itself during its transport down to the boot's location. Literature references had mentioned that material had a tendency to segregate according to particle size and particle weight. Heavier particles tend to fall out of suspension easier than lighter particles, contact the conveying tube wall, then slow down relative to suspended particles due to the effect of the wall friction. The net effect in a very long transport tube was that the finer particles arrived prior to the heavier particles. In the case of pneumatic transport of fertilizer, the tube length was relatively short, but long enough for some particles to strike the tube wall, slow down, and arrive at the boot location as a random pneumatic flow. Further literature review indicated Kidd (1972) had patented

a rotary valve like device to act as a normal distribution manifold on a pneumatic grain drill.

Evidently, in order to be effective, any nesting device would have to be located as close as possible to the boot. For the device to be mounted near the boot it would have to be small, rugged, and as simple as possible since one would be required on each run.

6.3 Oscillating Gates

To fill these requirements an electrically operated solenoid oscillating gate was developed. Duration and frequency of the gate openings were controlled by a timing circuit. Early test runs indicated this type of system had limitations. Very short open durations did not allow all the material on the gate to fall through, and blocking resulted. Once the open duration requirements were filled, the maximum available frequencies were limited.

Initially the objective for nest placement was one nest every 300 mm. Coupling 300 mm spacing with a field speed of 5.5 km/h required nearly 5 cycles per second from the nesting device. Experiments were conducted in a range near 5 gate openings per second and high speed films taken. The high speed films were taken at 250 and 400 frames per second with a film marker being applied to the film ten times per second. Events on the film could then be timed by counting frames on the film, and counting the number of frames

between film marker spots. Sizes of nests and lengths of spaces between nests could then be extrapolated simply by observing the urea granules against a 10 mm by 10 mm background grid and multiplying the time interval by the planned forward velocity.

Examination of the films quickly indicated the material did not stay in neat clumps as the gate opened, rather fertilizer tended to strike the sides during its fall and redistribution occurred after the fertilizer left the boot. Data were taken as 80, 90, and 95 percent of the fertilizer granules which would make up one nest were passing a reference point located where the fertilizer would leave the boot in a field application. Tests with above 95 percent of the material in a nest were not practical, since some fertilizer granules were always scattered between clumps (figure 6.1). While working with forestry grade urea, the total number of granules in a nest could be counted, and the granules for 80, 90, and 95 percent of the total also could be counted (figure 6.2). In the case of nesting with small granules, an estimation for each percentage of the total nest had to be made (figure 6.3).

Averages for the four different gate open durations (50, 40, 30, and 20 percent of gate oscillation period) are given in table 6.1 for small granules, and table 6.2 for forestry grade granules. Graphically, the effect of different gate open durations for small granule urea and forestry grade urea can be seen in figure 6.4 and figure

Figure 6.1 Small urea granules scattered between nest clumps

Figure 6.2 A single frame of high speed film showing a nest of forestry urea granules

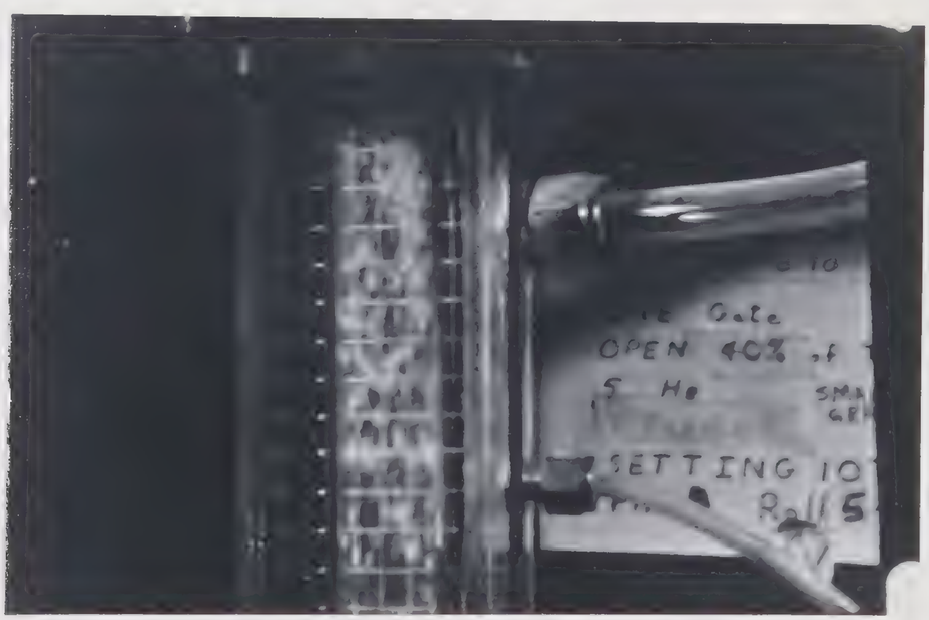


Figure 6.3 A single frame of high speed film showing a nest of small urea granules

Table 6.1 Effect of gate open duration on the accumulation interval of small urea granules

Period = 0.20 seconds

All times are in seconds

S.D. = standard deviation

Gate Open Duration		Percent of Fertilizer Granules Past the Reference Line		
		80%	90%	95%
	Mean	0.048	0.065	0.083
50%	S.D.	0.0064	0.0061	0.0045
	Mean	0.042	0.055	0.066
40%	S.D.	0.0065	0.0091	0.0094
	Mean	0.049	0.055	0.096
30%	S.D.	0.0097	0.0099	0.0094
	Mean	0.048	0.065	0.087
20%	S.D.	0.0060	0.0073	0.0071

Table 6.2 Effect of gate open duration on the accumulation interval of forestry urea granules

Period = 0.20 seconds

All times are in seconds

S.D. = standard deviation

Gate Open Duration		Percent of Fertilizer Granules Past the Reference Line		
		80%	90%	95%
50%	Mean	0.060	0.075	0.092
	S.D.	0.0067	0.0118	0.0180
40%	Mean	0.052	0.070	0.088
	S.D.	0.0174	0.0214	0.0216
30%	Mean	0.064	0.098	0.120
	S.D.	0.0288	0.0251	0.0309
20%	Mean	0.071	0.096	0.117
	S.D.	0.0167	0.0176	0.0133

6.5, respectively.

Surprisingly, a gate opening duration of 40 percent of the gate's period resulted in a statistically significant smaller projected nest size for both fertilizer granule sizes than did either the gate open durations of 30 or 20 percent. Possibly the downward air flow through the tube while the gate was open tended to push the fertilizer granules down the tube in a clump.

6.3.1 Air Blasts

To test the theory of air flow helping to move the material downward in a clump, a second two-solenoid gate device was developed. The lower gate operated in an identical fashion to the single gate unit. Above the first gate was a small chamber complete with a second solenoid operated gate constructed so as to block the escape path for the transporting air when the second gate closed (figure 6.6). Therefore when the second gate closed, air was trapped in the chamber above the lower gate, which was collecting urea granules. Whenever the lower gate opened, with the upper gate closed, an air blast from the air conveying the fertilizer granules assisted the fertilizer granules down past the lower gate.

Three timing sequences were tried for the operations of the second gate. The first, called "no delay", consisted of operating both gates simultaneously, with the upper gate closing causing an air blast at the same instant the lower

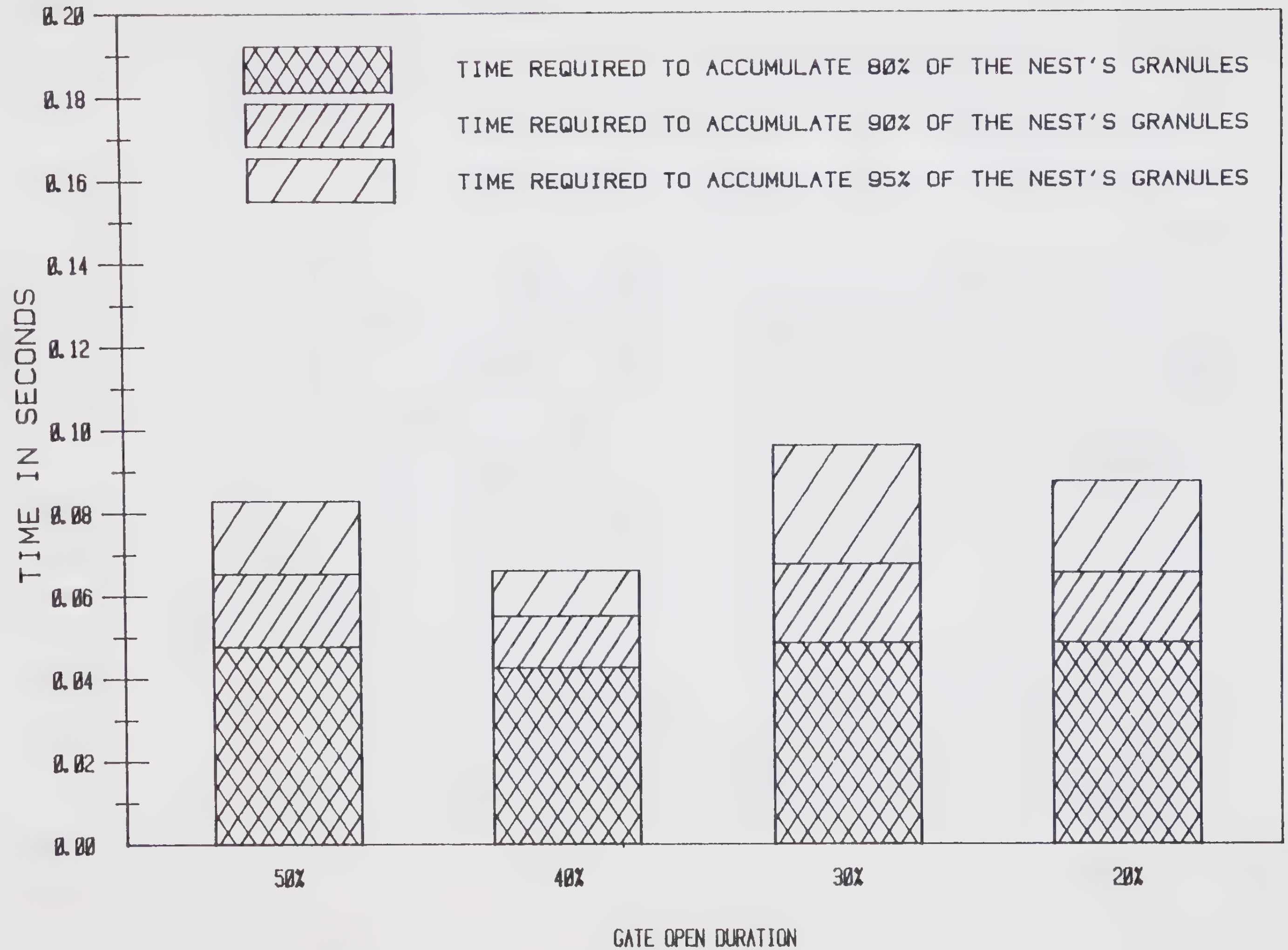


Figure 6.4 Effect of gate open duration on the accumulation interval of small urea granules

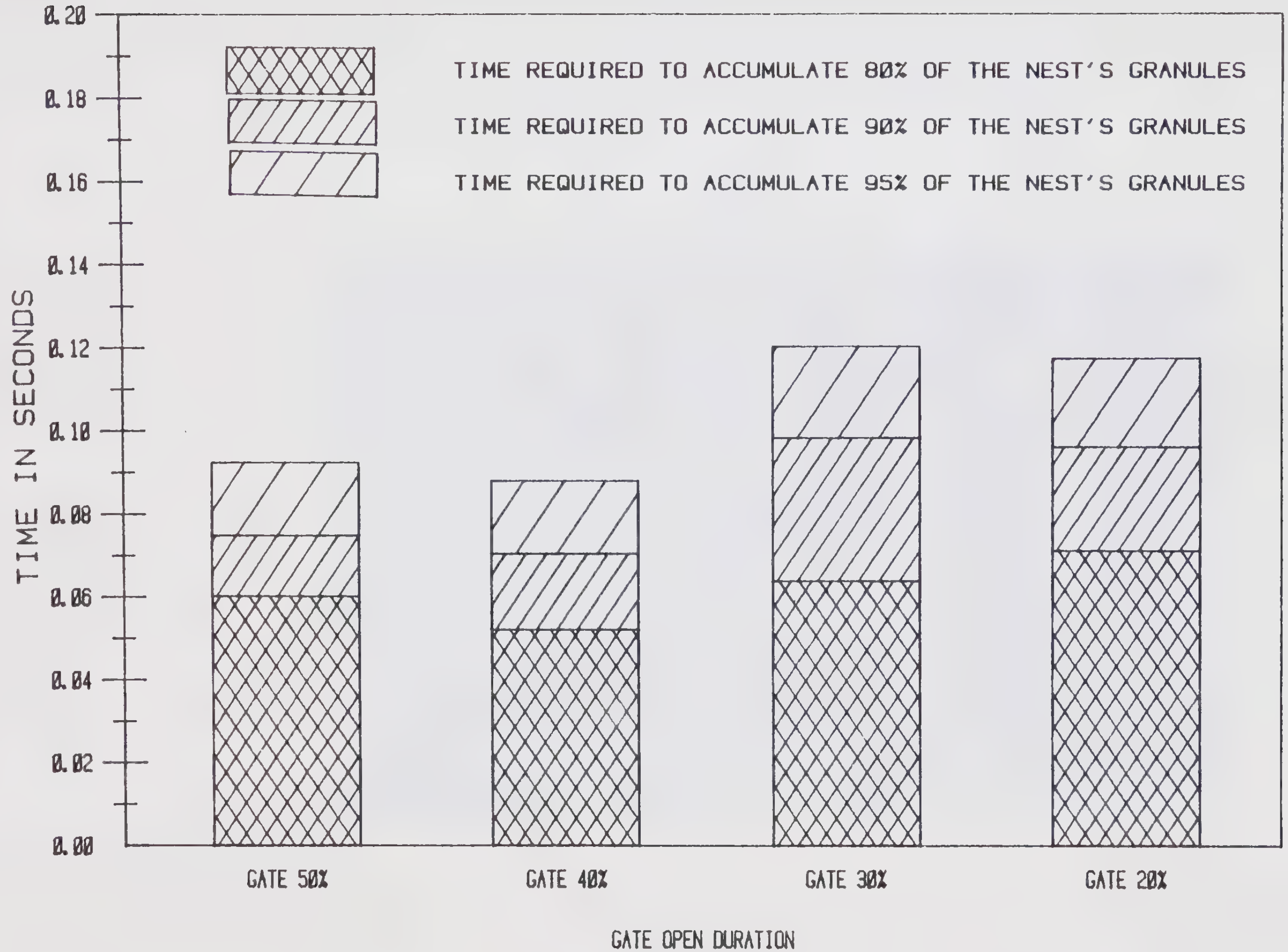


Figure 6.5 Effect of gate open duration on the accumulation interval of forestry urea granules

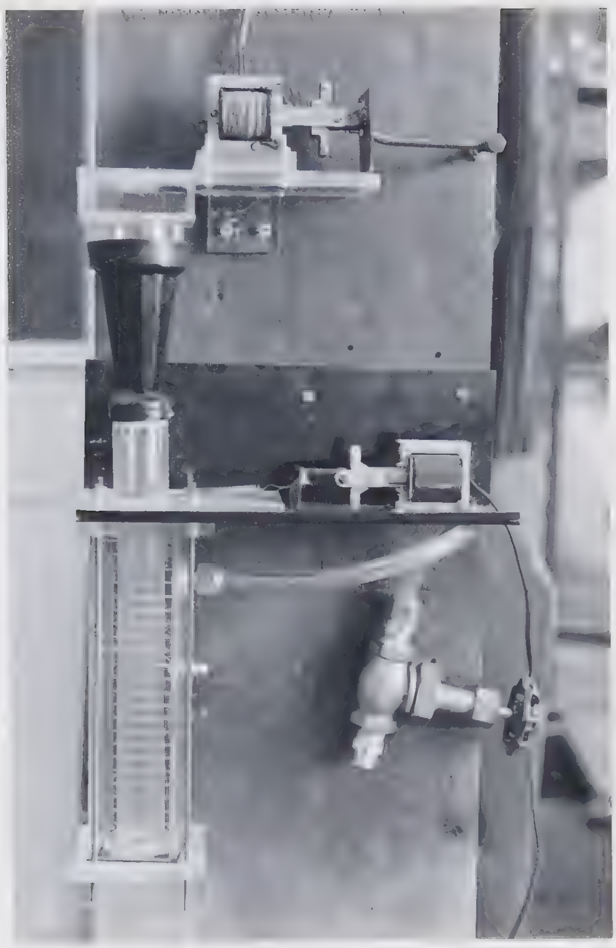


Figure 6.6 Twin oscillating gate air blast device

gate opened. The second, a timing sequence referred to as "20 percent lead", consisted of the upper gate closing for a time interval equal to 20 percent of the gate open duration before the lower gate opened. Finally, a timing sequence called "20 percent lag", consisted of closing the upper gate a time interval equal to 20 percent of the lower gate's open duration, after the lower gate opened.

Each of the above timing sequences was tried with the lower gate operating at a 30 percent open duration. The effects of no delay, 20 percent lead, and 20 percent lag time sequences were compared to the effect of a single gate operating at a 30 percent open duration (called a "check"), as seen in table 6.3 for small granules and table 6.4 for forestry grade granules. Graphically, the effect of the three different air blast timings may be seen in figure 6.7 for small granules and figure 6.8 for forestry granules.

For the small granules, all the air blast timings had a statistically significant effect in compressing the nest size. In fact, any form of air blast resulted in 90 percent of the granules being placed in less than 25 percent of the inter-nest spacing. Of the three timings attempted, no delay and 20 percent lag were the most effective in compressing the nest size.

Forestry grade granules also had their nest size compressed by the use of an air blast (although not by a statistically significant amount). The air blast benefit was most noticeable on 90 percent and 95 percent levels of the

Table 6.3 Effect of an air blast on the accumulation interval of small urea granules

Period = 0.20 seconds

All times are in seconds

S.D. = standard deviation

Inter-gate Timing		Percent of Fertilizer Granules Past the Reference Line		
		80%	90%	95%
Check	Mean	0.049	0.055	0.096
	S.D.	0.0097	0.0099	0.0094
No Delay	Mean	0.038	0.048	0.058
	S.D.	0.0049	0.0064	0.0077
20% Lead	Mean	0.041	0.048	0.058
	S.D.	0.0092	0.0101	0.0119
20% Lag	Mean	0.037	0.045	0.054
	S.D.	0.0042	0.0050	0.0062

Table 6.4 Effect of an air blast on the accumulation interval of forestry urea granules

Period = 0.20 seconds

All times are in seconds

S.D. = standard deviation

Inter-gate Timing		Percent of Fertilizer Granules Past the Reference Line		
		80%	90%	95%
Check	Mean	0.064	0.098	0.120
	S.D.	0.0288	0.0251	0.0309
No Delay	Mean	0.065	0.085	0.101
	S.D.	0.0161	0.0165	0.0212
20% Lead	Mean	0.060	0.086	0.101
	S.D.	0.0168	0.0239	0.0192
20% Lag	Mean	0.060	0.086	0.101
	S.D.	0.0168	0.0239	0.0192

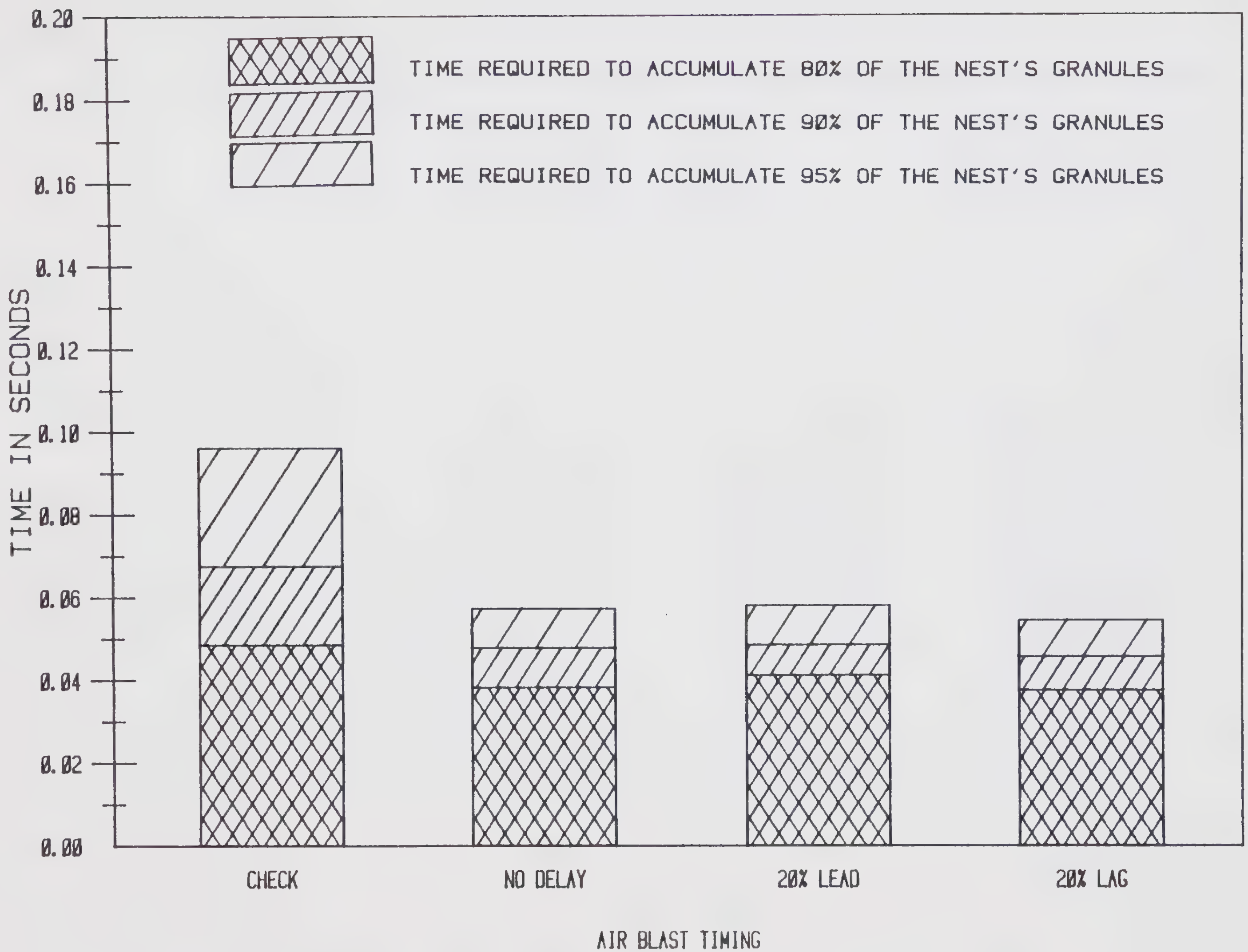


Figure 6.7 Effect of an air blast on the accumulation interval of small urea granules

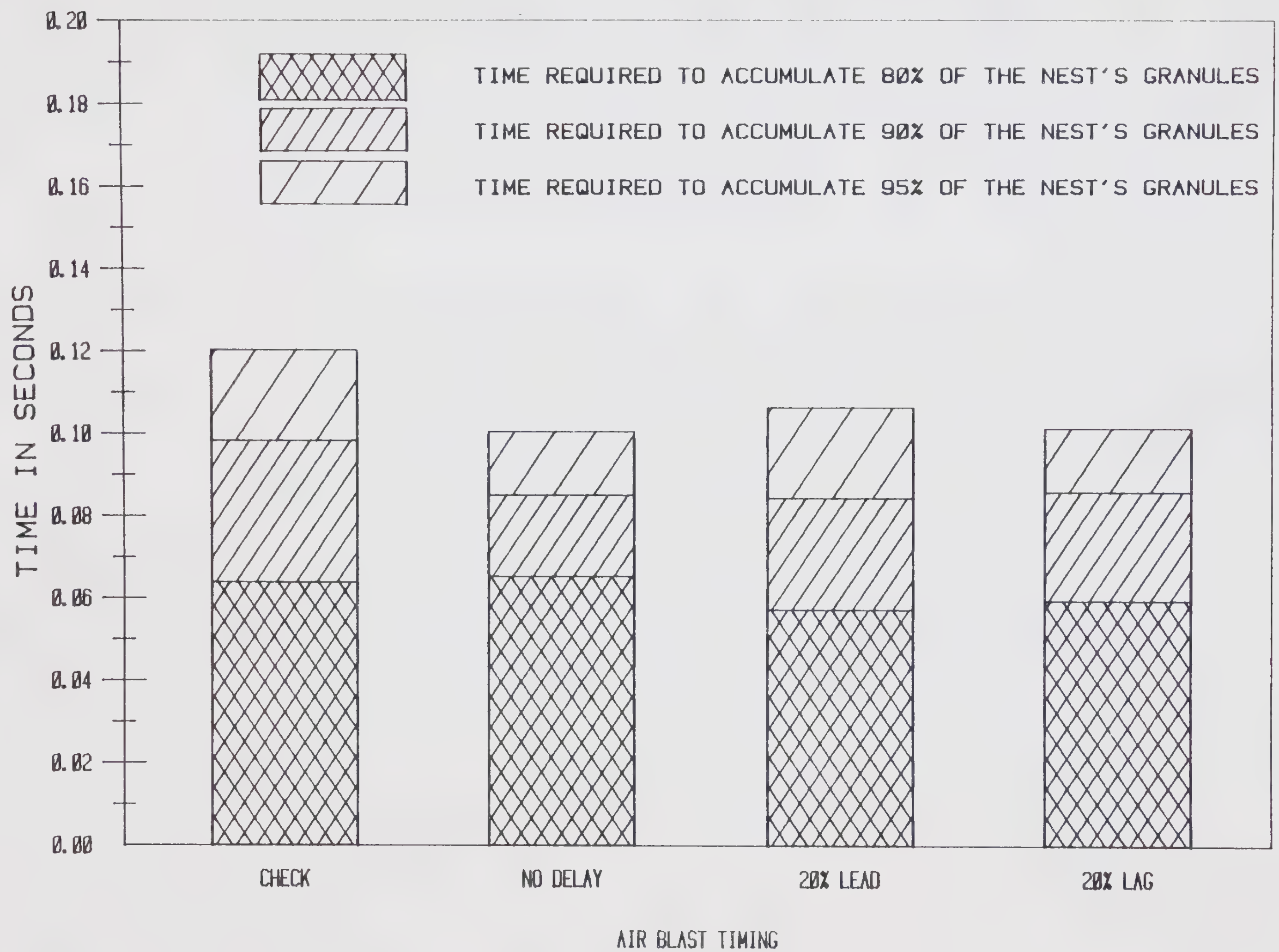


Figure 6.8 Effect of an air blast on the accumulation interval of forestry urea granules

granules in a nest. Again a 20 percent lead in the air blast timing was the least effective in compressing the nest size.

6.3.2 Air Cushion Tubes

Two tubes with different sized holes (0.8 millimetres and 1.6 millimetres in diameter) were developed which introduced higher pressure air through small holes along the tube's length. The air was introduced along the inner walls of the tube to form an air cushion which was to prevent particles from striking the tube walls and then redistributing themselves along the tube length.

Results of using the air cushion tubes were mixed. Data collected from observing fertilizer granules flowing down tubes equipped to provide an air cushion were compared to data collected from observing fertilizer granules flowing down normal tubes (referred to as a "check"). The time period to pass 80 percent of the nest's material down the air-cushioned tube was always longer than the time period to pass 80 percent of the nest's material down the original tube. The time period to pass 95 percent of the material down the tube was shorter using either of the two test tubes for the small granules. In the case of forestry grade granules only the small diameter holes in the tube shortened the time period to pass 95 percent of the material down the tube. Effects of the air cushion tubes on small granule urea are given in table 6.5 and graphically illustrated in figure 6.9, while the effects on forestry grade urea granules are

Table 6.5 Effect of an air cushion on the accumulation interval of small urea granules

Period = 0.20 seconds

All times are in seconds

S.D. = standard deviation

Air Cushion Type		Percent of Fertilizer Granules Past the Reference Line		
		80%	90%	95%
Check	Mean	0.049	0.068	0.096
	S.D.	0.0097	0.0099	0.0094
Small Holes	Mean	0.059	0.071	0.084
	S.D.	0.0073	0.0091	0.0077
Large Holes	Mean	0.055	0.068	0.083
	S.D.	0.0073	0.0077	0.0082

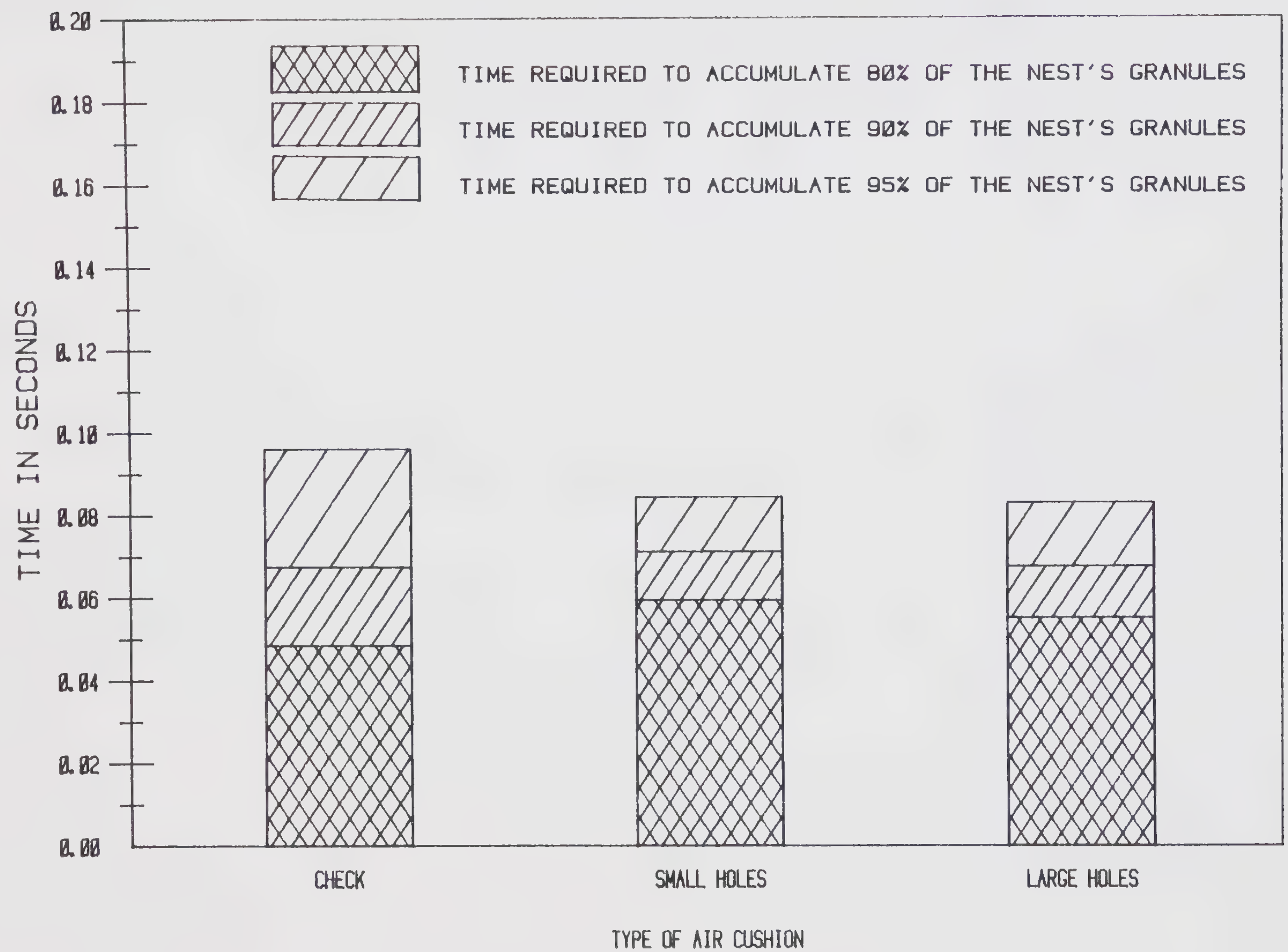


Figure 6.9 Effect of an air cushion on the accumulation interval of small urea granules

Table 6.6 Effect of an air cushion on the accumulation interval of forestry urea granules

Period = 0.20 seconds

All times are in seconds

S.D. = standard deviation

Air Cushion Type		Percent of Fertilizer Granules Past the Reference Line		
		80%	90%	95%
Check	Mean	0.064	0.098	0.120
	S.D.	0.0288	0.0251	0.0309
Small Holes	Mean	0.069	0.089	0.101
	S.D.	0.0090	0.0171	0.0187
Large Holes	Mean	0.085	0.103	0.119
	S.D.	0.0189	0.0124	0.0119

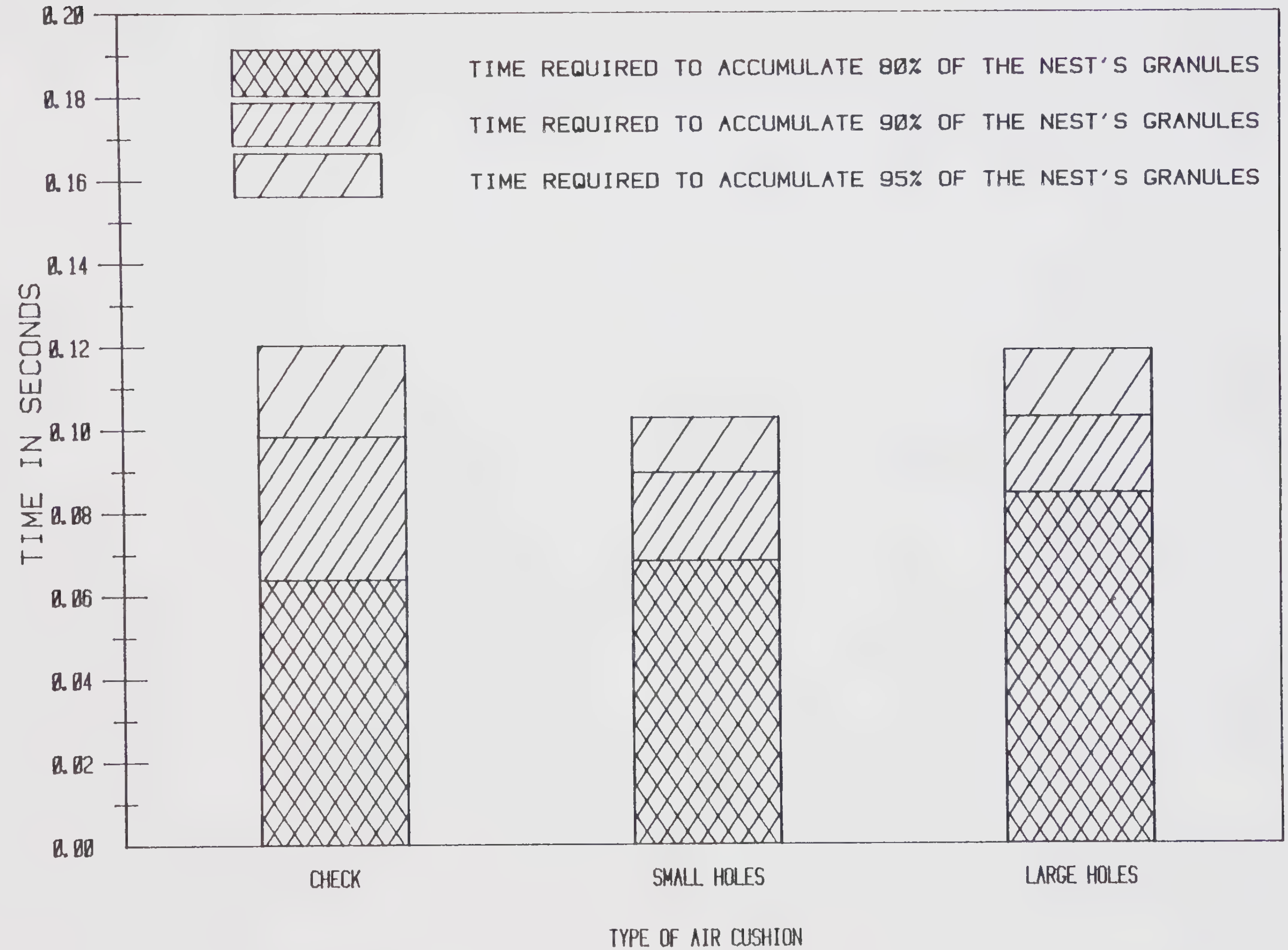


Figure 6.10 Effect of an air cushion on the accumulation interval of forestry urea granules

given in table 6.6 and in figure 6.10.

Examination of the above tables and figures gave no indication of air cushions significantly compressing the nest size. Statistically the air cushion did significantly compress the nest size at the 80% level, but the significance was lost at the 90% and 95% levels. For that reason no further studies of the air cushion tubes were undertaken.

7. Summary and Conclusions

1. Pneumatic transport of particulate materials is an expanding science which has encompassed agricultural applications. Unfortunately the majority of modern research into the engineering principles of pneumatic transport of particles has utilized particulate materials found in industrial rather than agricultural applications. A void in scientific knowledge applicable to the pneumatic transport of agricultural products has resulted. Research should be undertaken to study the engineering principles of pneumatic transport of agricultural products such as fertilizers.
2. The distance a clump or nest of fertilizer granules could be transported after being formed was severely limited by the tendency of the fertilizer granules to redistribute themselves randomly along any tube within which they were being pneumatically transported. For "pneumatic fertilizer nesters" the above statement eliminates the possibility of utilizing any centrally located rotary valve to form nests of granular fertilizer. Furthermore since redistribution begins taking place immediately, most methods of pneumatic fertilizer nesting will experience some redistribution between the location where the nest's fertilizer granules are collected, and the final placement of the fertilizer granule nest.
3. Small urea granules, commonly used by farmers in the

Canadian prairie provinces, produced smaller projected nest sizes than did forestry urea granules under laboratory tests.

4. Use of a single oscillating gate mechanism in conjunction with small urea granules produced nests (containing 90 percent of the metered nest's material) that covered less than 30 percent of the inter-nest spacing.
5. Use of an "air blast" mechanism in conjunction with small urea granules produced nests (containing 90 percent of the metered nest's material) that covered less than 25 percent of the inter-nest spacing.
6. Use of an air cushion in the boot tube appeared to have limited application, since nest size was not significantly reduced.
7. The research results obtained indicate that concentrating more than 90 percent of a nest's material into less than 25 percent of the inter-nest spacing would be exceedingly difficult to accomplish in commercial practice.

8. Recommendations for Further Work

Experience gained during this project has highlighted a need for further research in the following areas:

1. A study should be undertaken to establish friction factors associated with the pneumatic transport of different fertilizers in:
   a. Horizontal pipes
   b. Vertical pipes
   c. Inclined pipes
   d. Bends

   Particular interest should be placed on the particle acceleration zone, which is near where the fertilizer is introduced into the airflow.
2. Agronomic studies should be undertaken to establish the optimum shape and size of the fertilizer nest. Further studies should be made to compare the effect of using different granule sizes in bands and nests.
3. Agronomic and engineering studies should be undertaken in the utilization of super granules such as those produced by Norsk Hydro under North American conditions.

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APPENDICES

Appendix A-1: Sieve Analysis of Small Urea Granules

Screen mesh	Nominal sieve opening (mm)	Percent of material retained on screen
#4	4.76	0.0
#8	2.38	24.7
#10	2.00	57.1
#12	1.68	13.3
#16	1.18	4.3
#18	1.00	.3
#20	.841	.1
Pan	0.00	.2

Forestry granule urea density = 786 g/L *

Geometric mean diameter following ASAE standard S319 formula:

$$d_m = \log^{-1} \left[\frac{\Sigma (W_i \log d_o)}{\Sigma W_i} \right]$$

d_m = geometric mean diameter

W_i = weight fraction on i'th sieve

d_o = geometric mean diameter of particles on i'th sieve

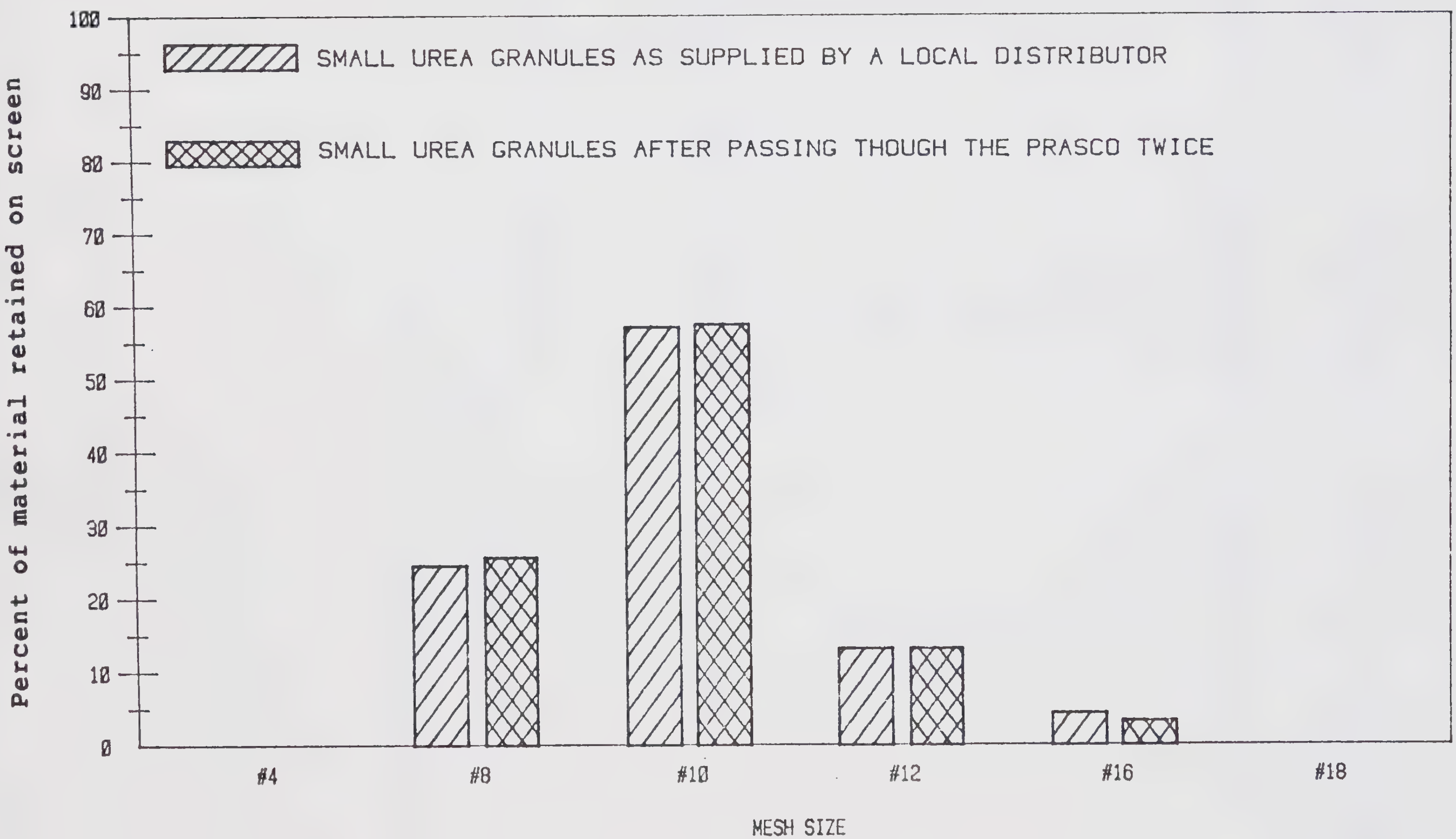
$= (d_i \times d_{i+1})^{1/2}$

d_i = diameter of sieve openings of the i'th sieve

Geometric mean diameter = 1.80 mm

----

* Fertilizer densities were determined by gently pouring 1000 mL of fertilizer into a graduated cylinder, then weighing the 1000 mL of fertilizer.



Appendix A-1: Sieve Analysis of Small Urea Granules

Appendix A-2: Sieve Analysis of Forestry Urea Granules

Screen mesh	Nominal sieve opening (mm)	Percent of material retained on screen
#4	4.76	34.9
#8	2.38	60.6
#14	1.40	4.1
#16	1.18	trace
#20	.841	trace
Pan	0.00	trace

Forestry granule urea density = 749 g/L *

Geometric mean diameter following ASAE standard S319 formula:

$$d_m = \log^{-1}\left[\frac{\Sigma\,(W_i \log d_o)}{\Sigma\, W_i}\right]$$

d_m = geometric mean diameter

W_i = weight fraction on i'th sieve

d_o = geometric mean diameter of particles on i'th sieve

$= (d_i \times d_{i+1})^{1/2}$

d_i = diameter of sieve openings of the i'th sieve

Geometric mean diameter = 2.86 mm

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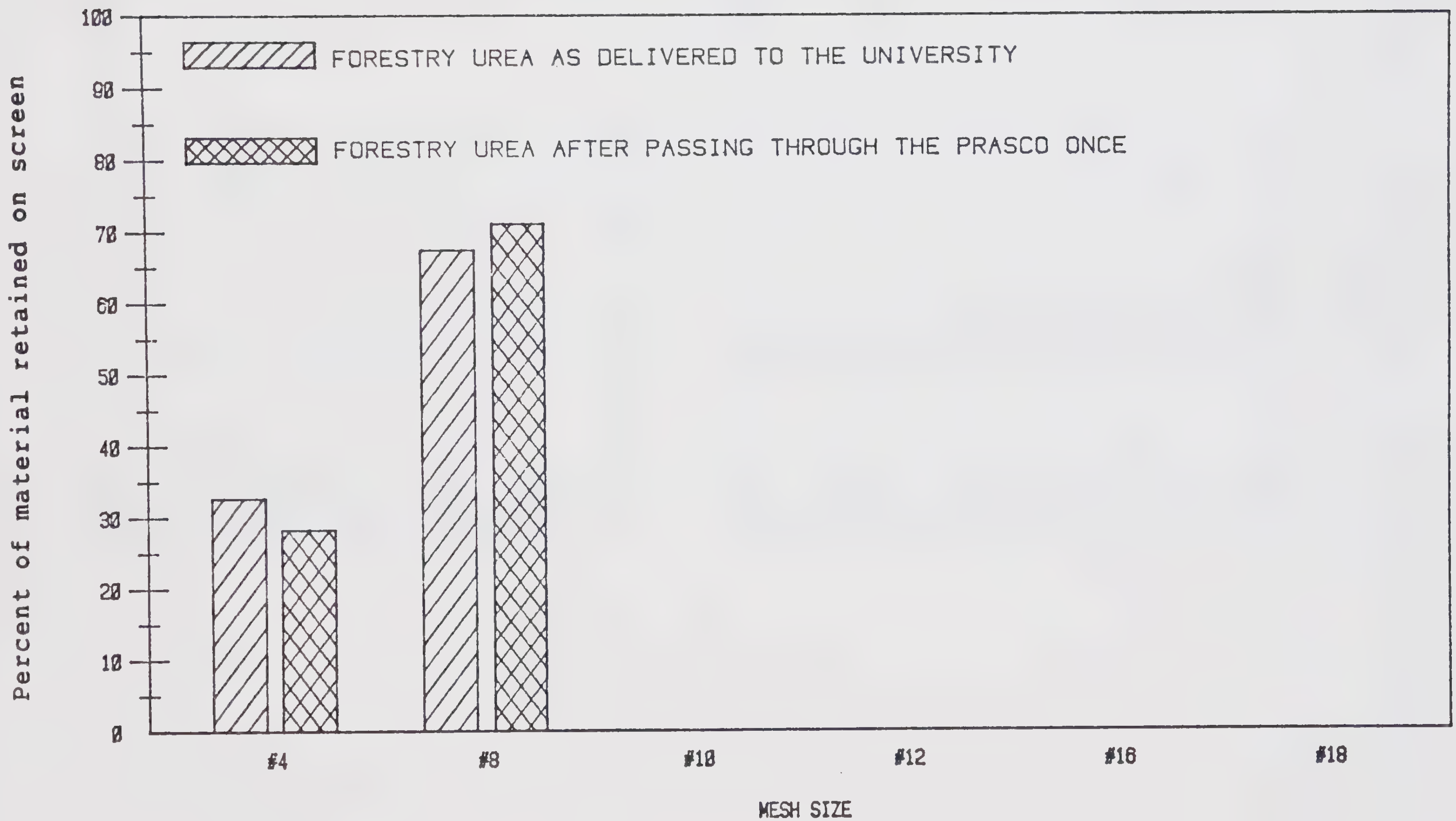
* Fertilizer densities were determined by gently pouring 1000 mL of fertilizer into a graduated cylinder, then weighing the 1000 mL of fertilizer.



Appendix A-2: Sieve Analysis of Forestry Urea Granules

Appendix B-1: Data for Different Gate Open Durations Using Small Granule Urea

50% Gate open Duration

	80%	90%	95%
	0.04140	0.05860	0.07590
	0.05170	0.06900	0.08620
	0.04830	0.06550	0.08970
	0.04140	0.06550	0.08280
	0.04140	0.05520	0.08280
	0.05520	0.07240	0.08280
	0.05520	0.06900	0.07930
Average	0.04780	0.06503	0.08279

40% Gate open Duration

	80%	90%	95%
	0.03100	0.03790	0.04480
	0.04480	0.06550	0.07930
	0.04140	0.05170	0.06210
	0.04480	0.05860	0.06550
	0.03790	0.05170	0.06550
	0.05170	0.06210	0.07240
	0.04480	0.05860	0.07240
Average	0.04234	0.05516	0.06600

30% Gate open Duration

	80%	90%	95%
	0.03450	0.05520	0.07590
	0.05860	0.07590	0.10340
	0.05170	0.07240	0.09660
	0.04830	0.06550	0.10000
	0.06210	0.08280	0.10340
	0.04480	0.06210	0.09660
	0.04140	0.05860	0.09660
Average	0.04877	0.06750	0.09607

20% Gate open Duration

	80%	90%	95%
	0.04480	0.05520	0.07930
	0.05170	0.06550	0.08620
	0.04140	0.05860	0.09660
	0.04480	0.06210	0.07930
	0.05860	0.07590	0.09310
	0.05170	0.06550	0.08280
	0.04480	0.07240	0.09310
Average	0.04826	0.06503	0.08720

Appendix B-2: Data for Different Gate Open Durations Using Forestry Urea

Data for Gate Durations 50%

	80%	90%	95%
	0.05200	0.06000	0.06400
	0.05090	0.06180	0.07270
	0.06780	0.08470	0.10170
	0.06210	0.06900	0.10000
	0.06550	0.08970	0.10690
	0.06440	0.08470	0.11190
	0.05780	0.07460	0.08810
Average	0.06007	0.07493	0.09219

Data for Gate Durations 40%

	80%	90%	95%
	0.06880	0.09380	0.10000
	0.03080	0.04620	0.06150
	0.03180	0.04090	0.05910
	0.07600	0.09600	0.11600
	0.06040	0.07920	0.09810
	0.05260	0.07020	0.08070
	0.04590	0.06560	0.10160
Average	0.05233	0.07027	0.08814

Data for Gate Durations 30%

	80%	90%	95%
	0.08650	0.11890	0.14590
	0.10000	0.12730	0.15910
	0.09360	0.10640	0.13190
	0.04230	0.09230	0.11920
	0.05260	0.08770	0.09470
	0.04000	0.10550	0.12360
	0.03050	0.05080	0.06780
Average	0.06364	0.09841	0.12031

Data for Gate Durations 20%

	80%	90%	95%
	0.07500	0.10000	0.11500
	0.06520	0.08200	0.10000
	0.08000	0.10400	0.11200
	0.04730	0.06550	0.11270
	0.06440	0.10170	0.12200
	0.09670	0.11670	0.14000
	0.07140	0.09580	0.11700
Average	0.07143	0.09510	0.11696

Appendix C-1: Data for the Effect of an Air Blast on Small Urea Granules

Check

	80%	90%	95%
	0.03450	0.05520	0.07590
	0.05860	0.07590	0.10340
	0.05170	0.07240	0.09660
	0.04830	0.06550	0.10000
	0.06210	0.08280	0.10340
	0.04480	0.06210	0.09660
	0.04140	0.05860	0.09660
Average	0.04877	0.06750	0.09607

No Delay

	80%	90%	95%
	0.03450	0.04140	0.05170
	0.04480	0.05860	0.06900
	0.03450	0.04480	0.05170
	0.03790	0.04480	0.05170
	0.04140	0.05170	0.06210
	0.03100	0.04140	0.05170
	0.04140	0.05170	0.06550
Average	0.03793	0.04777	0.05763

20% Lead

	80%	90%	95%
	0.03450	0.03790	0.04480
	0.04140	0.04830	0.05860
	0.03450	0.04480	0.05860
	0.02760	0.03450	0.04140
	0.05170	0.05860	0.06550
	0.05170	0.06210	0.07590
	0.04480	0.05170	0.06210
Average	0.04089	0.04827	0.05813

20% Lag

	80%	90%	95%
	0.03790	0.04480	0.04830
	0.03450	0.04480	0.05520
	0.04480	0.05520	0.06550
	0.03450	0.04140	0.05170
	0.03450	0.04140	0.04830
	0.03450	0.04140	0.05170
	0.04140	0.04830	0.05860
Average	0.03744	0.04533	0.05419

Appendix C-2: Data for the Effect of an Air Blast on Forestry Urea Granules

Check

	80%	90%	95%
	0.08650	0.11890	0.14590
	0.10000	0.12730	0.15910
	0.09360	0.10640	0.13190
	0.04230	0.09230	0.11920
	0.05260	0.08770	0.09470
	0.04000	0.10550	0.12360
	0.03050	0.05080	0.06780
Average	0.06364	0.09841	0.12031

No Delay

	80%	90%	95%
	0.06050	0.06980	0.07910
	0.04900	0.07350	0.08750
	0.04150	0.06420	0.07920
	0.06550	0.08280	0.09660
	0.07240	0.10000	0.13100
	0.08330	0.09670	0.11000
	0.08330	0.10670	0.12330
Average	0.06507	0.08481	0.10096

20% Lead

	80%	90%	95%
	0.03180	0.05450	0.09090
	0.04800	0.08000	0.09200
	0.07030	0.09630	0.12600
	0.06670	0.09470	0.10200
	0.06330	0.09000	0.11000
	0.05250	0.08200	0.09510
	0.06670	0.09470	0.13000
Average	0.05704	0.08460	0.10657

20% Lag

	80%	90%	95%
	0.05670	0.08330	0.09670
	0.07000	0.10330	0.11670
	0.04140	0.04830	0.08280
	0.06440	0.10170	0.10850
	0.03330	0.05670	0.07000
	0.07120	0.09830	0.10850
	0.07930	0.10690	0.12410
Average	0.05947	0.08550	0.10104

Appendix D-1: Data for the Effect of an Air Cushion on Small Urea Granules

Check

	80%	90%	95%
	0.08650	0.11890	0.14590
	0.10000	0.12730	0.15910
	0.09360	0.10640	0.13190
	0.04230	0.09230	0.11920
	0.05260	0.08770	0.09470
	0.04000	0.10550	0.12360
	0.03050	0.05080	0.06780
Average	0.06364	0.09841	0.12031

Small Holes

	80%	90%	95%
	0.07590	0.10000	0.10690
	0.07240	0.08280	0.09310
	0.06550	0.11720	0.13440
	0.06900	0.08620	0.10000
	0.07930	0.09660	0.10690
	0.05170	0.06550	0.07590
	0.06550	0.07590	0.08620
Average	0.06847	0.08917	0.10049

Large Holes

	80%	90%	95%
	0.07950	0.08970	0.12410
	0.11030	0.12070	0.13100
	0.07240	0.08970	0.10000
	0.10000	0.11720	0.13100
	0.08280	0.09660	0.11030
	0.09660	0.10340	0.11030
	0.05520	0.10000	0.12400
Average	0.08526	0.10247	0.11867

Appendix D-2: Data for the Effect of an Air Cushion on Forestry Urea Granules

Check

	80%	90%	95%
	0.08650	0.11890	0.14590
	0.10000	0.12730	0.15910
	0.09360	0.10640	0.13190
	0.04230	0.09230	0.11920
	0.05260	0.08770	0.09470
	0.04000	0.10550	0.12360
	0.03050	0.05080	0.06780
Average	0.06364	0.09841	0.12031

Small Holes

	80%	90%	95%
	0.07590	0.10000	0.10690
	0.07240	0.08280	0.09310
	0.06550	0.11720	0.13440
	0.06900	0.08620	0.10000
	0.07930	0.09660	0.10690
	0.05170	0.06550	0.07590
	0.06550	0.07590	0.08620
Average	0.06847	0.08917	0.10049

Large Holes

	80%	90%	95%
	0.07950	0.08970	0.12410
	0.11030	0.12070	0.13100
	0.07240	0.08970	0.10000
	0.10000	0.11720	0.13100
	0.08280	0.09660	0.11030
	0.09660	0.10340	0.11030
	0.05520	0.10000	0.12400
Average	0.08526	0.10247	0.11867

Appendix E-1: Statistical Analysis of the Effect of Gate Open Duration on the Projected Nest Size of Small Urea Granules at the 80% Level

table values are in seconds

table rows represent sample for gate open durations of 50%,40%,30% and 20% respectively

0.0414	0.0517	0.0483	0.0414	0.0414	0.0552	0.0552
0.031	0.0448	0.0414	0.0448	0.0379	0.0517	0.0448
0.0345	0.0586	0.0517	0.0483	0.0621	0.0448	0.0414
0.0448	0.0517	0.0414	0.0448	0.0586	0.0517	0.0448

Output from the Anova Package

A	3	.00019	.00006
ERROR	24	.00127	.00005
TOTAL	27	.00146	

Output from the Duncan Package

IDENTIFICATION	MEAN
2	.048
1	.042
4	.049
3	.048

1 2 3 4

Appendix E-2: Statistical Analysis of the Effect of Gate Open Duration on the Projected Nest Size of Small Urea Granules at the 90% Level

table values are in seconds

table rows represent sample for gate open durations of 50%,40%,30% and 20% respectively

0.0586	0.069	0.0655	0.0655	0.0552	0.0724	0.069
0.0379	0.0655	0.0517	0.0586	0.0517	0.0621	0.0586
0.0552	0.0759	0.0724	0.0655	0.0828	0.0621	0.0586
0.0552	0.0655	0.0586	0.0621	0.0759	0.0655	0.0724

Output from the Anova Package

A	3	.00063	.00021
ERROR	24	.00164	.00007
TOTAL	27	.00227	

Output from the Duncan Package

IDENTIFICATION	MEAN
2	.065
1	.055
4	.068
3	.065

1 2 3 4

Appendix E-3: Statistical Analysis of the Effect of Gate Open Duration on the Projected Nest Size of Small Urea Granules at the 95% Level

table values are in seconds

table rows represent sample for gate open durations of 50%,40%,30% and 20% respectively

0.0759	0.0862	0.0897	0.0828	0.0828	0.0828	0.0793
0.0448	0.0793	0.0621	0.0655	0.0655	0.0724	0.0724
0.0759	0.1034	0.0966	0.1	0.1034	0.0966	0.0966
0.0793	0.0862	0.0966	0.0793	0.0931	0.0828	0.0931

Output from the Anova Package

A	3	.00334	.00111
ERROR	24	.00168	.00007
TOTAL	27	.00502	

Output from the Duncan Package

IDENTIFICATION	MEAN
2	.083
1	.066
4	.096
3	.087

1 2 3 4

Appendix E-4: Statistical Analysis of the Effect of Gate Open Duration on the Projected Nest Size of Forestry Urea Granules at the 80% Level

table values are in seconds

table rows represent sample for gate open durations of 50%,40%,30% and 20% respectively

0.052	0.0509	0.0678	0.0621	0.0655	0.0644	0.0578
0.0688	0.0308	0.0318	0.076	0.0604	0.0526	0.0459
0.0865	0.1	0.0936	0.0423	0.0526	0.04	0.0305
0.075	0.0652	0.08	0.0473	0.0644	0.0967	0.0714

Output from the Anova Package

A	3	.00132	.00044
ERROR	24	.00846	.00035
TOTAL	27	.00978	

Output from the Duncan Package

IDENTIFICATION	MEAN
2	.060
1	.052
3	.064
4	.071

1 2 3 4

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Appendix E-5: Statistical Analysis of the Effect of Gate Open Duration on the Projected Nest Size of Forestry Urea Granules at the 90% Level

table values are in seconds

table rows represent sample for gate open durations of 50%,40%,30% and 20% respectively

0.06	0.0618	0.0847	0.069	0.0897	0.0847	0.0746
0.0938	0.0462	0.0409	0.096	0.0792	0.0702	0.0656
0.1189	0.1273	0.1064	0.0923	0.0877	0.1055	0.0508
0.1	0.082	0.104	0.0655	0.1017	0.1167	0.0958

Output from the Anova Package

A	3	.00420	.00140
ERROR	24	.00905	.00038
TOTAL	27	.01325	

Output from the Duncan Package

IDENTIFICATION	MEAN
2	.075
1	.070
4	.098
3	.095

1 2 3 4

Appendix E-6: Statistical Analysis of the Effect of Gate Open Duration on the Projected Nest Size of Forestry Urea Granules at the 95% Level

table values are in seconds

table rows represent sample for gate open durations of 50%,40%,30% and 20% respectively

.0640	.0727	.1017	.1000	.1069	.1119	.0881
.1000	.0615	.0591	.1160	.0981	.0807	.1016
.1459	.1591	.1319	.1192	.0947	.1236	.0678
.1150	.1000	.1120	.1127	.1220	.1400	.1170

Output from the Anova Package

A	3	.00577	.00192
ERROR	24	.01136	.00047
TOTAL	27	.01713	

Output from the Duncan Package

IDENTIFICATION	MEAN
2	.092
1	.088
4	.120
3	.117

1 2 3 4

Appendix F-1: Statistical Analysis of the Effect of an Air Blast on the Projected Nest Size of Small Urea Granules at the 80% Level

table values are in seconds

table rows represent samples for check and air blast timings of no delay, 20% lead, and 20% lag respectively

0.0345	0.0586	0.0517	0.0483	0.0621	0.0448	0.0414
0.0345	0.0448	0.0345	0.0379	0.0414	0.031	0.0414
0.0345	0.0414	0.0345	0.0276	0.0517	0.0517	0.0448
0.0379	0.0345	0.0448	0.0345	0.0345	0.0345	0.0414

Output from the Anova Package

A	3	.00058	.00019
ERROR	24	.00131	.00005
TOTAL	27	.00189	

Output from the Duncan Package

IDENTIFICATION	MEAN
4	.049
2	.038
3	.041
1	.037

1 2 3 4

Appendix F-2: Statistical Analysis of the Effect of an Air Blast on the Projected Nest Size of Small Urea Granules at the 90% Level

table values are in seconds

table rows represent samples for check and air blast timings of no delay, 20% lead, and 20% lag respectively

0.0552	0.0759	0.0724	0.0655	0.0828	0.0621	0.0586
0.0414	0.0586	0.0448	0.0448	0.0517	0.0414	0.0517
0.0379	0.0483	0.0448	0.0345	0.0586	0.0621	0.0517
0.0448	0.0448	0.0552	0.0414	0.0414	0.0414	0.0483

Output from the Anova Package

A	3	.00221	.00074
ERROR	24	.00161	.00007
TOTAL	27	.00383	

Output from the Duncan Package

IDENTIFICATION	MEAN
4	.068
2	.048
3	.048
1	.045

1 2 3 4

Appendix F-3: Statistical Analysis of the Effect of an Air Blast on the Projected Nest Size of Small Urea Granules at the 95% Level

table values are in seconds

table rows represent samples for check and air blast timings of no delay, 20% lead and 20% lag respectively

0.0759	0.1034	0.0966	0.1	0.1034	0.0966	0.0966
0.0517	0.069	0.0517	0.0517	0.0621	0.0517	0.0655
0.0448	0.0586	0.0586	0.0414	0.0655	0.0759	0.0621
0.0483	0.0552	0.0655	0.0517	0.0483	0.0517	0.0586

Output from the Anova Package

A	3	.00822	.00274
ERROR	24	.00196	.00008
TOTAL	27	.01018	

Output from the Duncan Package

IDENTIFICATION	MEAN
4	.096
2	.058
3	.058
1	.054

1 2 3 4

Appendix F-4: Statistical Analysis of the Effect of an Air Blast on the Projected Nest Size of Forestry Urea Granules at the 80% Level

table values are in seconds

table rows represent samples for check and air blast timings of no delay, 20% lead, and 20% lag respectively

0.0865	0.1	0.0936	0.0423	0.0526	0.04	0.0305
0.0605	0.049	0.0415	0.0655	0.0724	0.0833	0.0833
0.0318	0.048	0.0703	0.0667	0.0633	0.0525	0.0667
0.0567	0.07	0.0414	0.0644	0.0333	0.0712	0.0793

Output from the Anova Package

A	3	.00029	.00010
ERROR	24	.00936	.00039
TOTAL	27	.00964	

Output from the Duncan Package

IDENTIFICATION	MEAN
3	.064
4	.065
1	.057
2	.059

1 2 3 4

Appendix F-5: Statistical Analysis of the Effect of an Air Blast on the Projected Nest Size of Forestry Urea Granules at the 90% Level

table values are in seconds

table rows represent samples for check and air blast timings of no delay, 20% lead, and 20% lag respectively

0.1189	0.1273	0.1064	0.0923	0.0877	0.1055	0.0508
0.0698	0.0735	0.0642	0.0828	0.1	0.0967	0.1067
0.0545	0.08	0.0963	0.0947	0.09	0.082	0.0947
0.0833	0.1033	0.0483	0.1017	0.0567	0.0983	0.1069

Output from the Anova Package

A	3	.00095	.00032
ERROR	24	.01014	.00042
TOTAL	27	.01110	

Output from the Duncan Package

IDENTIFICATION	MEAN
4	.098
2	.085
1	.085
3	.086

1 2 3 4

Appendix F-6: Statistical Analysis of the Effect of an Air Blast on the Projected Nest Size of Forestry Urea Granules at the 95% Level

table values are in seconds

table rows represent samples for check and air blast timings of no delay, 20% lead, and 20% lag respectively

0.1459	0.1591	0.1319	0.1192	0.0947	0.1236	0.0678
0.0791	0.0875	0.0792	0.0966	0.131	0.11	0.1233
0.0909	0.092	0.126	0.102	0.11	0.0951	0.13
0.0967	0.1167	0.0828	0.1085	0.07	0.1085	0.1241

Output from the Anova Package

A	3	.00174	.00058
ERROR	24	.01211	.00050
TOTAL	27	.01385	

Output from the Duncan Package

IDENTIFICATION	MEAN
4	.120
1	.101
3	.107
2	.101

1 2 3 4

Appendix G-1: Statistical Analysis of the Effect of an Air Cushion on the Projected Nest Size of Small Urea Granules at the 80% Level

table values are in seconds

table rows represent samples for check, small hole air cushions and large hole air cushions respectively

0.0345	0.0586	0.0517	0.0483	0.0621	0.0448	0.0414
0.0552	0.0621	0.0483	0.0517	0.0655	0.0655	0.0586
0.0517	0.0552	0.0483	0.0552	0.0448	0.0621	0.0655

Output from the Anova Package

A	2	.00031	.00016
ERROR	18	.00115	.00006
TOTAL	20	.00146	

Output from the Duncan Package

IDENTIFICATION	MEAN
1	.049
3	.058
2	.055

1 2 3

Appendix G-2: Statistical Analysis of the Effect of an Air Cushion on the Projected Nest Size of Small Urea Granules at the 90% Level

table values are in seconds

table rows represent samples for check, small hole air cushions and large hole air cushions respectively

0.0552	0.0759	0.0724	0.0655	0.0828	0.0621	0.0586
0.0655	0.0759	0.0586	0.0655	0.0862	0.0759	0.0724
0.0621	0.0655	0.0621	0.069	0.0586	0.0759	0.0793

Output from the Anova Package

A	2	.00007	.00004
ERROR	18	.00144	.00008
TOTAL	20	.00151	

Output from the Duncan Package

IDENTIFICATION	MEAN
2	.068
3	.071
1	.055

1 2 3

Appendix G-3: Statistical Analysis of the Effect of an Air Cushion on the Projected Nest Size of Small Urea Granules at the 95% Level

table values are in seconds

table rows represent samples for check, small hole air cushions and large hole air cushions respectively

0.0759	0.1034	0.0966	0.1	0.1034	0.0966	0.0966
0.0759	0.0897	0.0759	0.0793	0.0966	0.0862	0.0862
0.0724	0.0897	0.0759	0.0828	0.0759	0.0897	0.0931

Output from the Anova Package

A	2	.00074	.00037
ERROR	18	.00129	.00007
TOTAL	20	.00203	

Output from the Duncan Package

IDENTIFICATION	MEAN
3	.096
2	.084
1	.083

1 2 3

Appendix G-4: Statistical Analysis of the Effect of an Air Cushion on the Projected Nest Size of Forestry Urea Granules at the 80% Level

table values are in seconds

table rows represent samples for check, small hole air cushions and large hole air cushions respectively

0.0865	0.1	0.0936	0.0423	0.0526	0.04	0.0305
0.0759	0.0724	0.0655	0.069	0.0793	0.0517	0.0655
0.0795	0.1103	0.0724	0.1	0.0828	0.0966	0.0552

Output from the Anova Package

A	2	.00180	.00090
ERROR	18	.00754	.00042
TOTAL	20	.00935	

Output from the Duncan Package

IDENTIFICATION	MEAN
1	.064
2	.068
3	.085

1 2 3

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Appendix G-5: Statistical Analysis of the Effect of an Air Cushion on the Projected Nest Size of Forestry Urea Granules at the 90% Level

table values are in seconds

table rows represent samples for check, small hole air cushions and large hole air cushions respectively

0.1189	0.1273	0.1064	0.0923	0.0877	0.1055	0.0508
0.1	0.0828	0.1172	0.0862	0.0966	0.0655	0.0759
0.0897	0.1207	0.0897	0.1172	0.0966	0.1034	0.1

Output from the Anova Package

A	2	.00065	.00033
ERROR	18	.00645	.00036
TOTAL	20	.00710	

Output from the Duncan Package

IDENTIFICATION	MEAN
2	.098
1	.089
3	.102

1 2 3

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Appendix G-6: Statistical Analysis of the Effect of an Air Cushion on the Projected Nest Size of Forestry Urea Granules at the 95% Level

table values are in seconds

table rows represent samples for check, small hole air cushions and large hole air cushions respectively

0.1459	0.1591	0.1319	0.1192	0.0947	0.1236	0.0678
0.1069	0.0931	0.1344	0.1	0.1069	0.0759	0.0862
0.1241	0.131	0.1	0.131	0.1103	0.1103	0.124

Output from the Anova Package

A	2	.00170	.00085
ERROR	18	.00867	.00048
TOTAL	20	.01036	

Output from the Duncan Package

IDENTIFICATION	MEAN
3	.120
1	.100
2	.119

1 2 3

Appendix H: Fan Characteristics

	Air only	With Fertilizer
Fan speed	61.43 (r/s)	
Fertilizer flow	0.0 (kg/s)	.308 (kg/s)
Air flow (L/s)	229	155
* velocity in duct	28.2 m/s	19.1 m/s
Power (kW)	3.48	4.88
Static Pressure (mm water) W	320	393
Static Pressure (mm water) Z	257	323
Pressure loss between W & Z (mm water)	63	70
Atmospheric pressure (mm Hg)	700	
Intake air temperature dry bulb	23 degrees Celsius	
Intake air temperature wet bulb	17 degrees Celsius	

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* the total airflow into the fan was assumed to flow within the duct without a significant change of density

	Air only	With Fertilizer
Fan speed	59.77 (r/s)	
Fertilizer flow	0.0 (kg/s)	.320 (kg/s)
Air flow (L/s)	219	139
* velocity in duct	27.0 m/s	17.1m/s
Power (kW)	3.84	4.08
Static Pressure W (mm of water)	313	385
Static Pressure Z (mm of water)	255	319
Presssure loss between W & Z (mm of water)	58	66
Atmospheric pressure (mm Hg)	728	
Intake air temperature		
dry bulb	26.5 degrees Celsius	
wet bulb	17.5 degrees Celsius	

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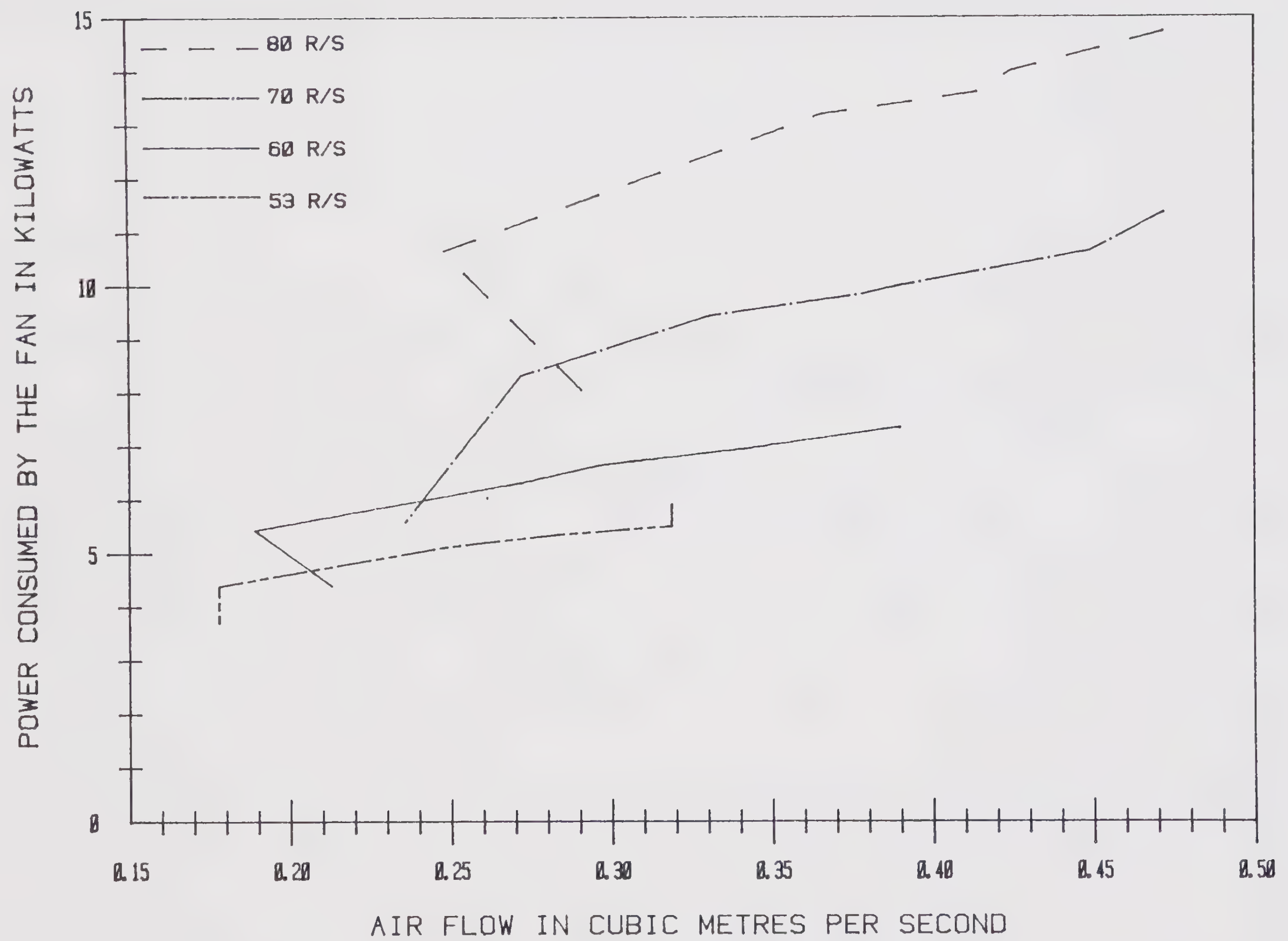
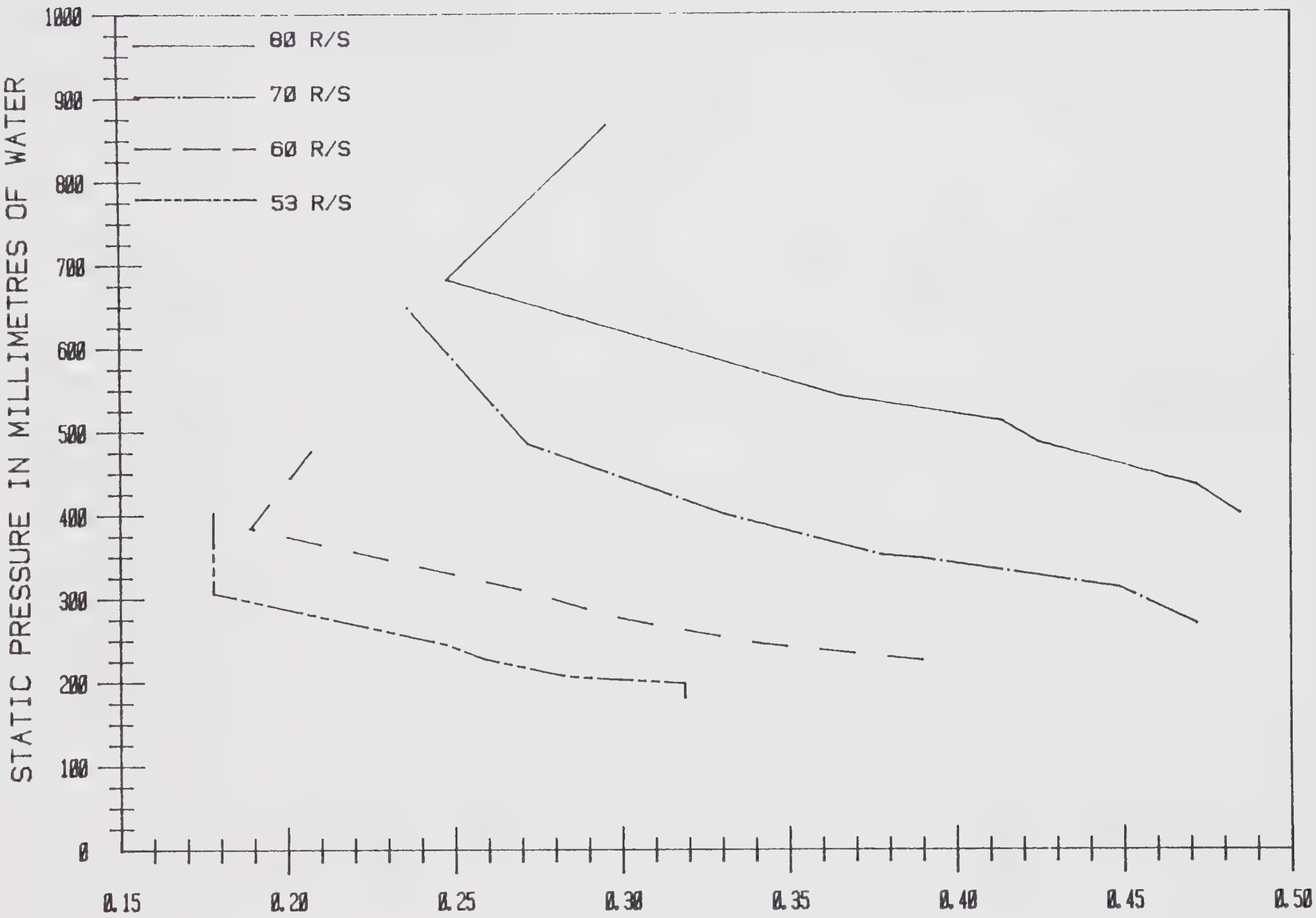
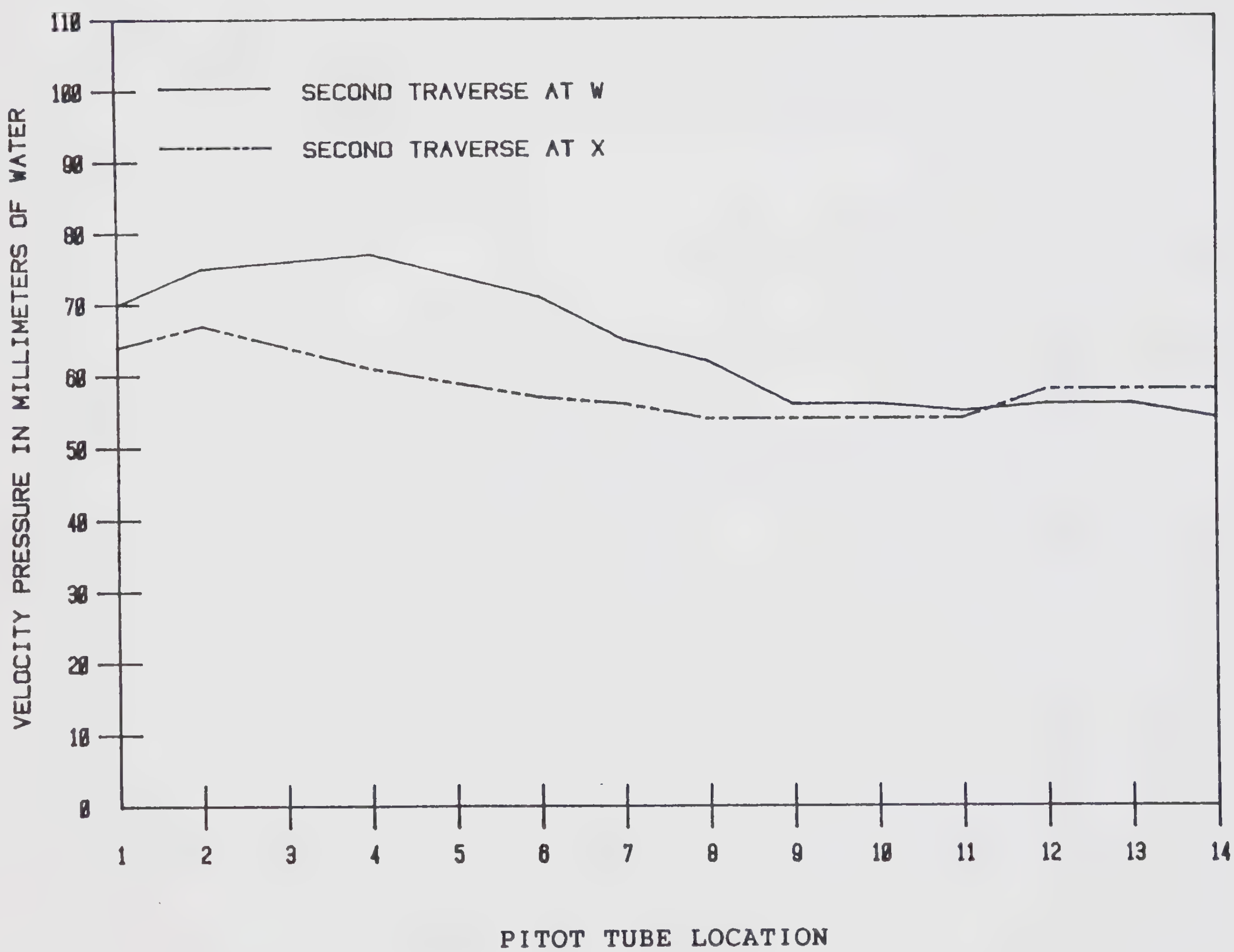
* the total airflow into the fan was assumed to flow within the duct without a significant change of density



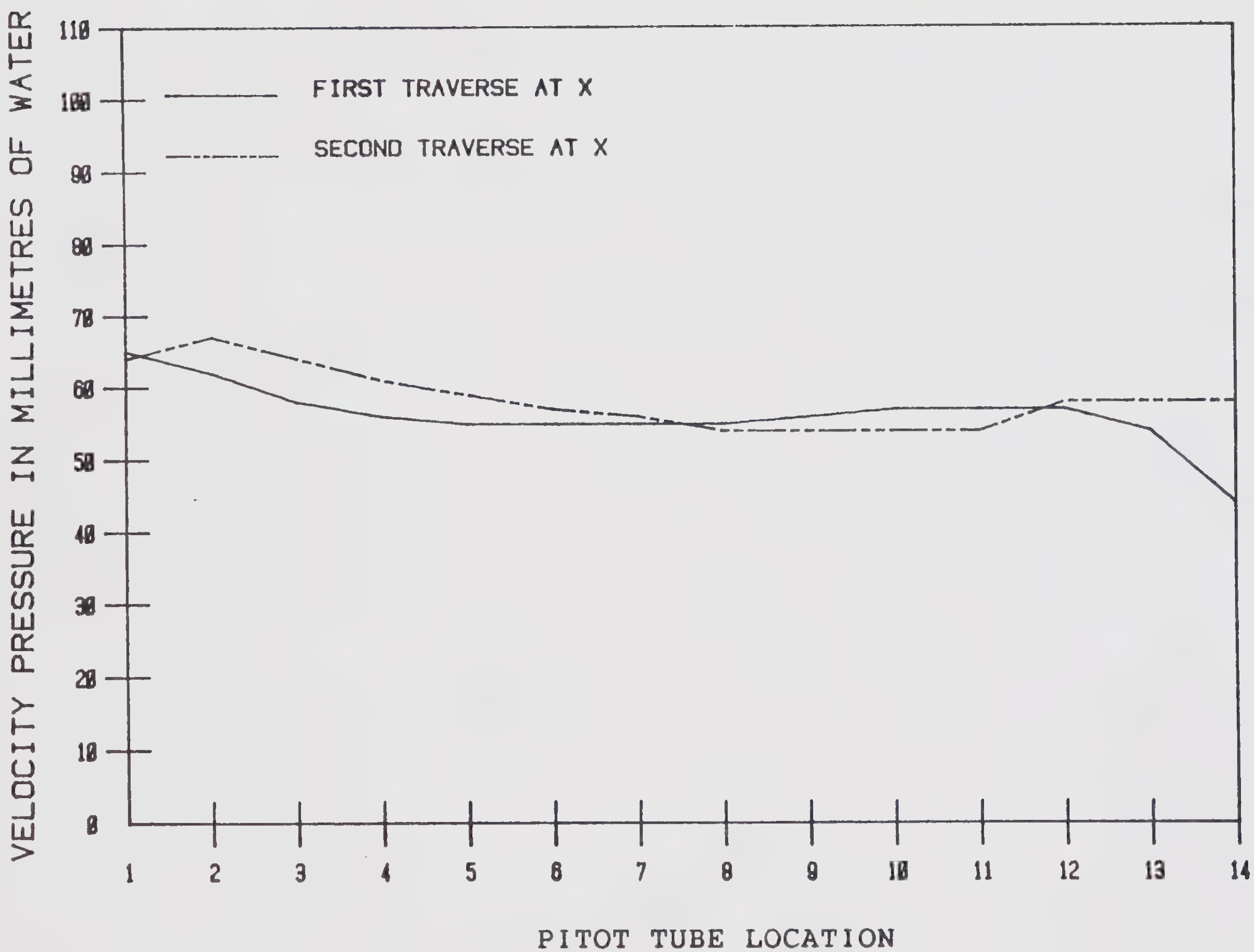
Appendix I-1: Fan Curves of Air Flow Versus Power



Appendix I-2: Fan Curves of Air Flow Versus Static



Appendix J-1: Comparison of Air Velocity Profiles Inside the Fertilizer Conveying Tube at Two Locations along the Tube



Appendix J-2: Comparison of Two Air Velocity Profiles Inside the Fertilizer Conveying Tube at One Location